HIGH FIELD PLASMONICS AND SOME APPLICATIONS

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(on behalf of the NAPLIFE Programme)

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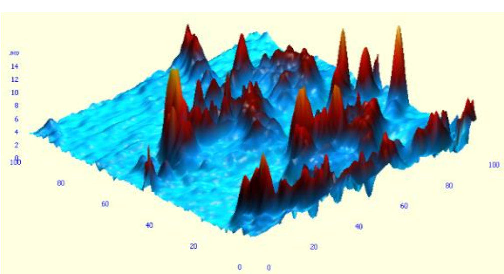
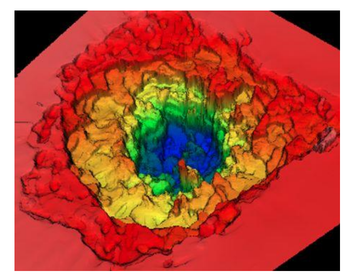
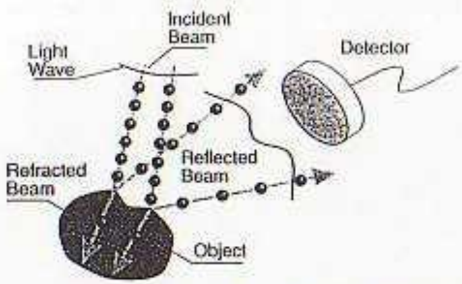
HUNGARIAN ACADEMY OF SCIENCES



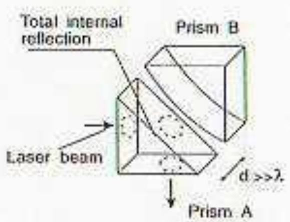
PP2023, 06.09.2023

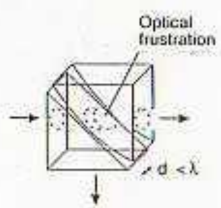


THE OPTICAL NEAR FIELD

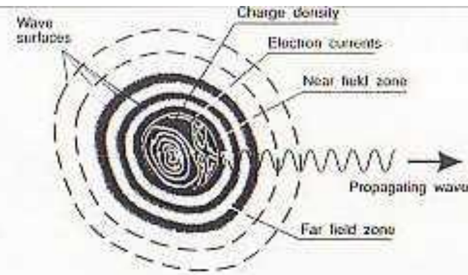


Schematic of the interaction between an object and a light beam. In first approximation, the light beam can be considered as projectiles launched against a target (the object) and then reflected towards the detector. This interpretation is primitive but provides the basis for the understanding of the notion of image.

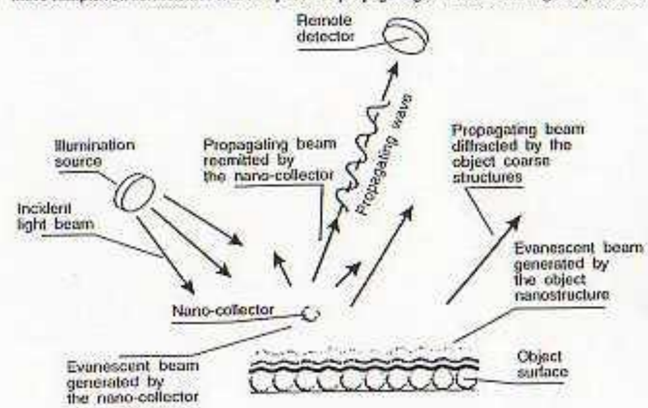


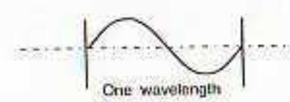


The famous experiment of Newton. A light beam is projected onto a prism. As expected, the beam is internally and totally reflected on the larger side of the prism. If a second prism is brought to the first one, no effect is detected unless the distance between the two prisms becomes smaller than a fraction of a micron. The light beam then seems to be captured by the second prism, frustrating the total reflection. The beam intensity transmitted through the second prism depends exponentially on the distance *d*.



Field emitted from an object. The electron currents (in the case of conducting materials) and the charge densities inside the object induce an electromagnetic field radiating from the surface. Far away from the surface the field has the well known structure of propagating waves. Very close to the object (the region of the question mark), the field has a more complex structure since it is composed of propagating and non-radiating components.

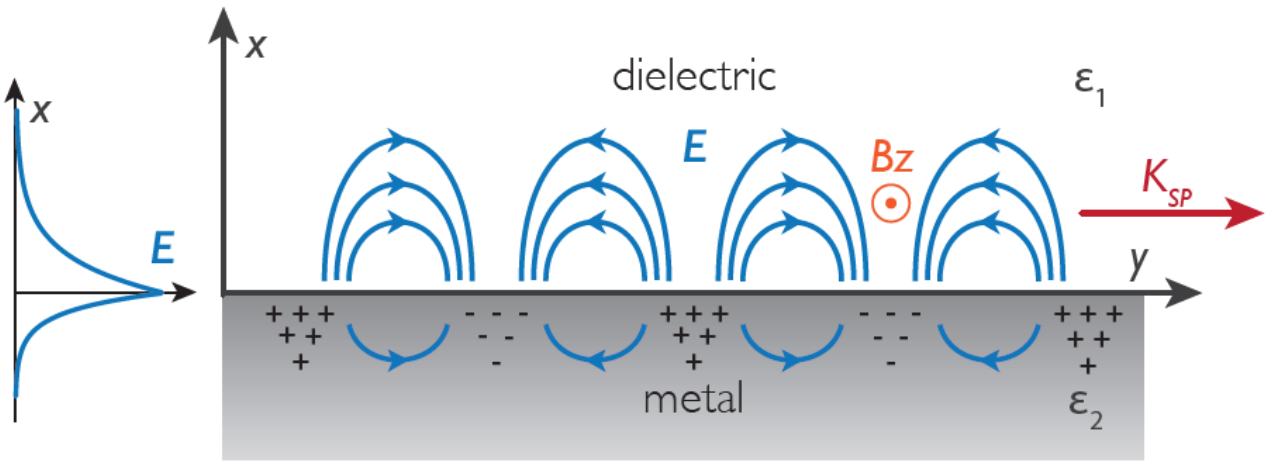




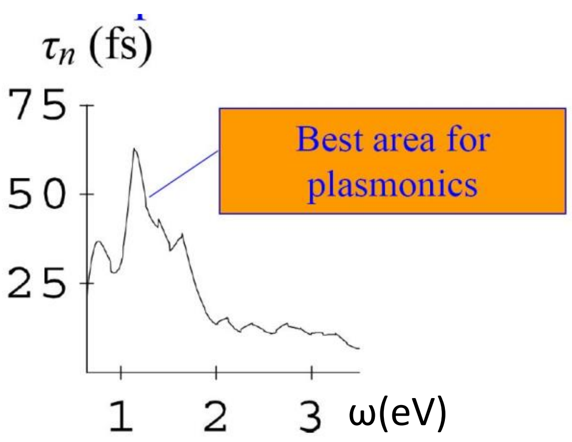
Sketch of near field detection. Step 1: generation of the object near field by the illumination process. A light source illuminates an object represented as composed of discrete components. These components are excited by the incident field and re-emit light. The waves associated to the reflected beam are composed of evanescent waves confined on the object surface and of propagating waves. If the periodic structures of the object are smaller than the wavelength (it is the case of the figure), the reflected field, far away from the object, does not contain any information on the fine structure of the object. Step 2: detection of the near field. For detecting the subwavelength object information, a small scattering centre (the nano-collector) is brought close enough to the object surface. The near field lying on the surface will excite the scattering centre which will re-emit light. The re-emitted light is again composed of evanescent waves (non-detectable) and propagating ones which can propagate far away to the remote detector.

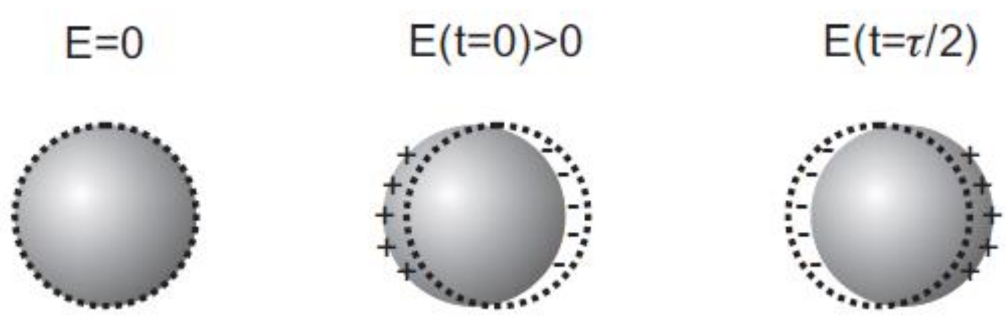
PLASMONICS AND HIGH FIELDS APPLICATIONS

Special type of the optical near field. **No diffraction limit.**



SPP

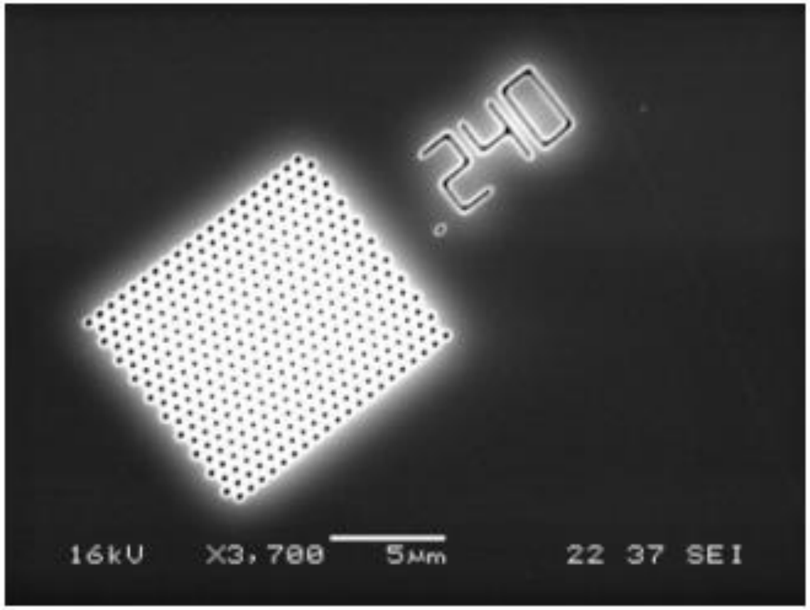


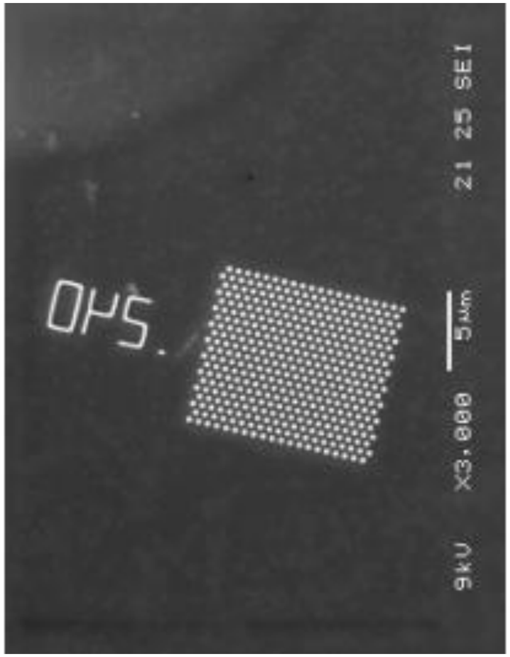


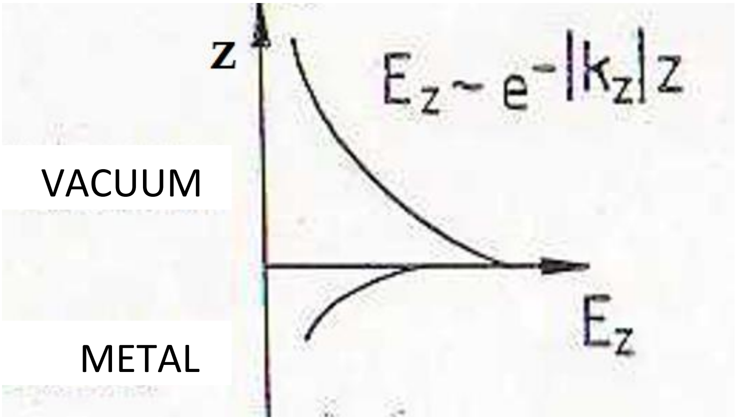
LSPP

Ti:Sa laser: Λ=800nm (~1.55eV) ; $t_{(SPP)}$~30fs

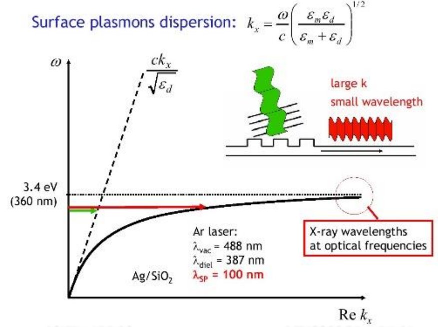
Light gets through the holes much smaller, than the wavelength of applied light.





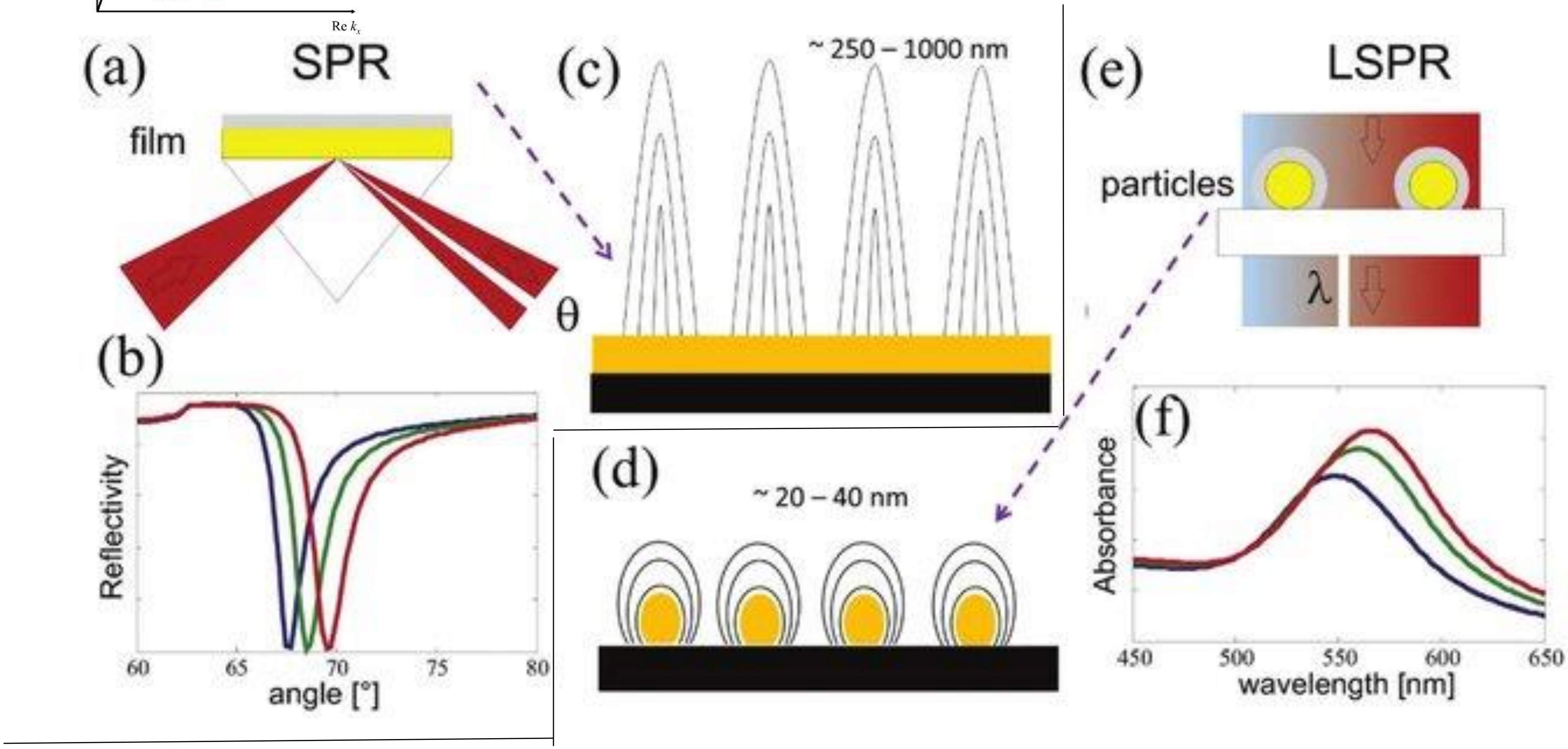


MOST OF THE ENERGY IS CONCENTRATED AT THE SURFACE:
GIANT FIELD ENHANCEMENT!



LOCALIZED PLASMONS (SPP andLSPP) UP TO 10^{20} W/cm^2)

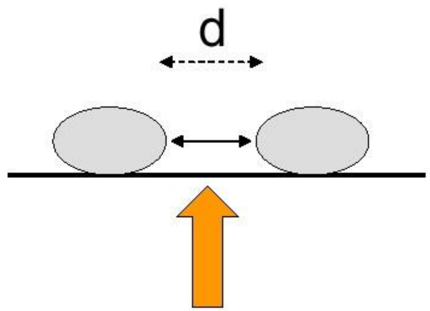
(The basic difference between SPP-s and LSPP-s)



LSPP: - NO EM FIELD PENETRATION INTO THE PLASMONIC MATERIAL (e.g. metal)

- SMALLER PENETRATION INTO THE DIELECTRIC /VACUUM
- NO DISPERSION
- BROADER RESONANCE

LSPP



d << λ

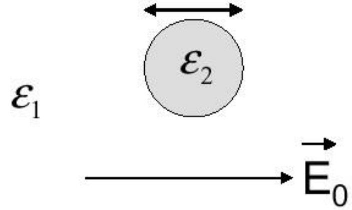
"Near-field coupling"

⇒ Resonator coupling

d >> λ

"Dipole-dipole coupling"

⇒ Interferences



If a << λ ⇒ dipole :

$$p = \varepsilon_2 \, \alpha \, E_0$$

with:

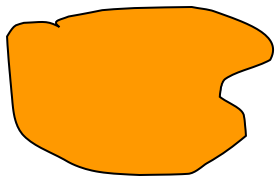
$$\alpha = 4\pi \, a^3 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}$$

Resonance when $\varepsilon_2(\omega) = -2 \times \varepsilon_1(\omega)$

- Enhanced absorption
- Enhancement of the near-field & scattering

PLASMON RESONANCE OF NANOPARTICLES SHAPE AND SIZE DEPENDENT!

$$\omega_B = \sqrt{\frac{4\pi e^2 n}{m_e}}$$

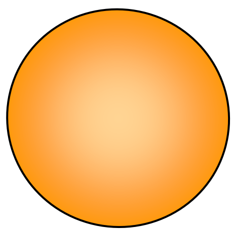


Bulk

$$\omega_{surf} = \frac{\omega_B}{\sqrt{2}}$$

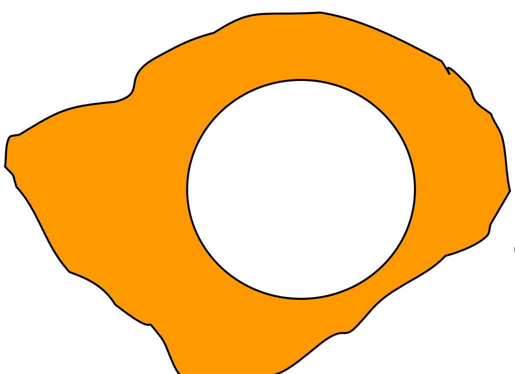
Surface

$$\omega_{S,l} = \omega_B \sqrt{\frac{l}{2l+1}}$$



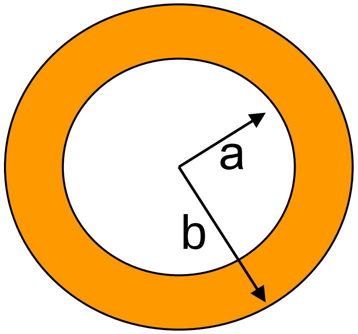
Sphere

Hole



$$\omega_{C,l} = \omega_B \sqrt{\frac{l+1}{2l+1}}$$

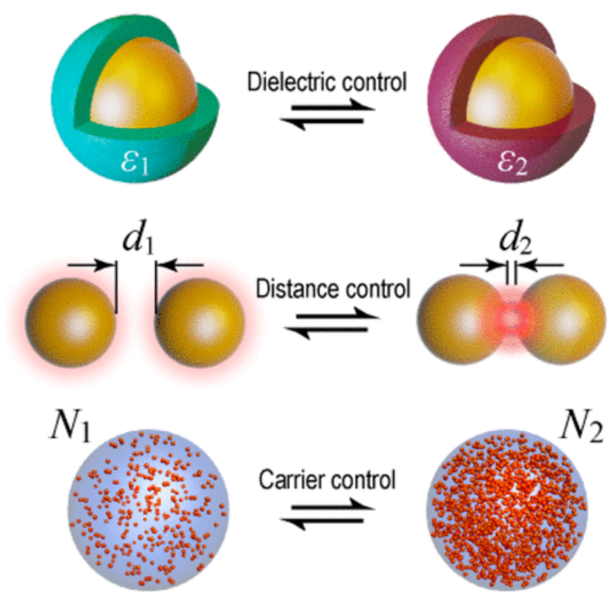
Nanoshell:



$$x = \frac{a}{b}$$

$$\omega_{l\pm}^2 = \frac{\omega_B^2}{2}\left[1 \pm \frac{1}{2l+1}\sqrt{1+4l(l+1)x^{2l+1}}\right]$$

Nanoshell plasmon resonance depends on the x ratio .



SPP and LSPP are a „NEW TYPE OF LIGHT”, they are

1. BOUND TO THE (METAL) SURFACE (SPP and LSPP)

2. HAVE SPECIFIC DISPERSION PROPERTIES (LSPP no dispersion)

3.THE DIFFRACTION LIMIT DOES NOT APPLY,

4.CAN BE SQUEEZED TO NANOSIZED VOLUMES

5. COULD REPRESENT VERY HIGH ELECTRIC FIELDS (hot spots)

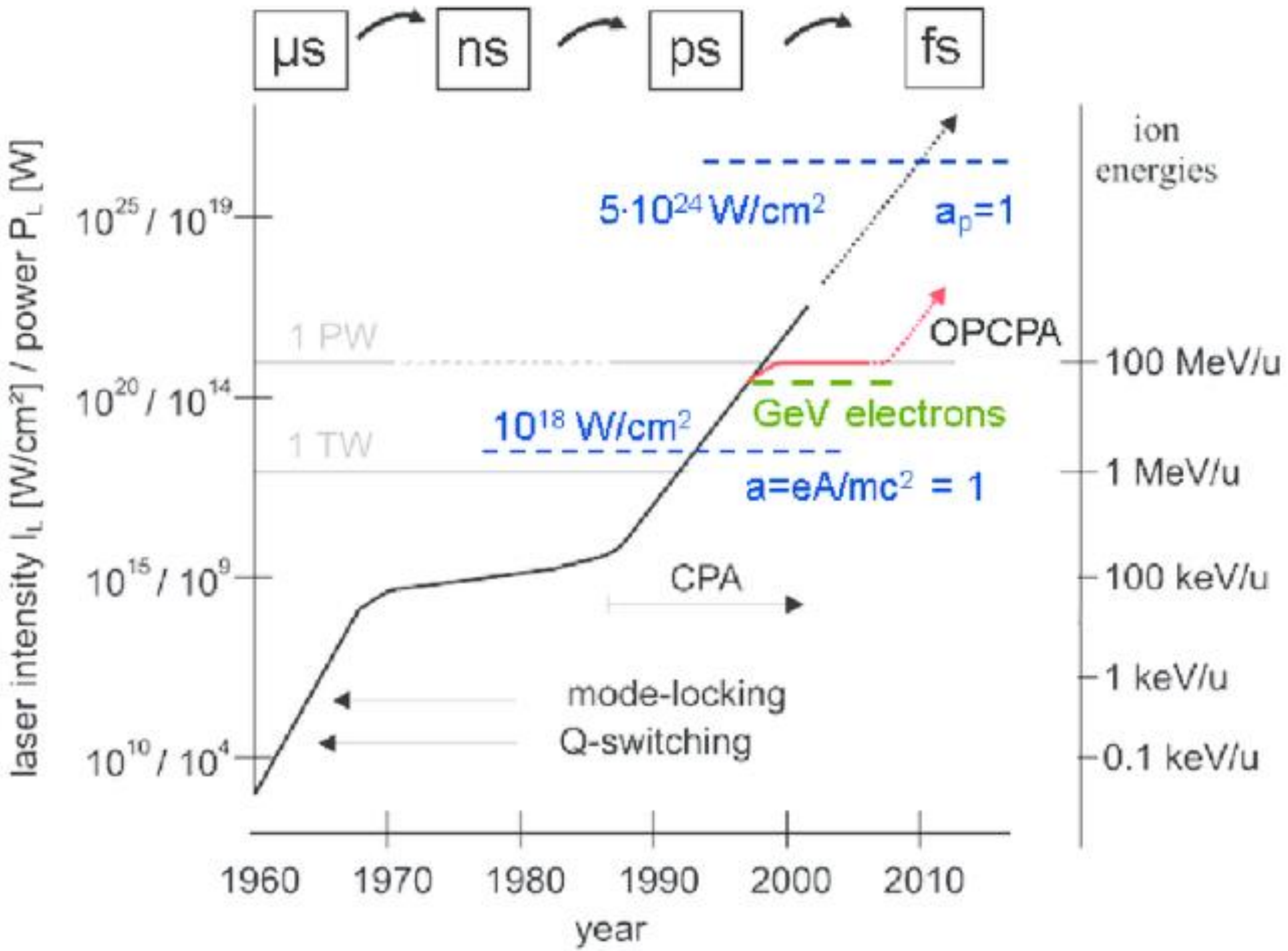
6. SCREEN POSITIVE (e.g.proton) PARTICLE CHARGES

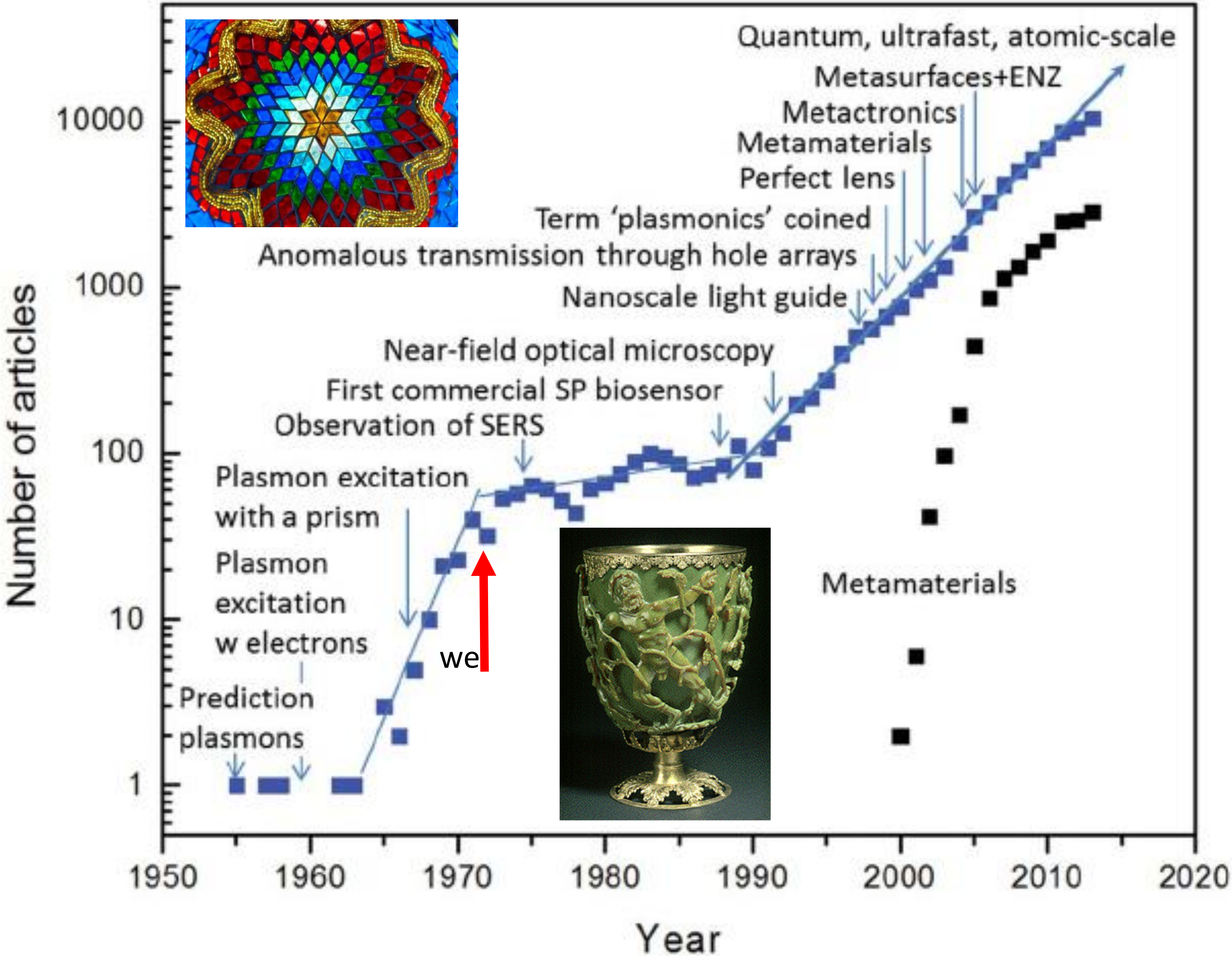
7. IS CORRELATED MOTION OF A HIGH NUMBER OF CONDUCTION ELECTRONS

8. MAY BE THE SOURCE OF DIFFERENT NONLINEAR PROCESSES

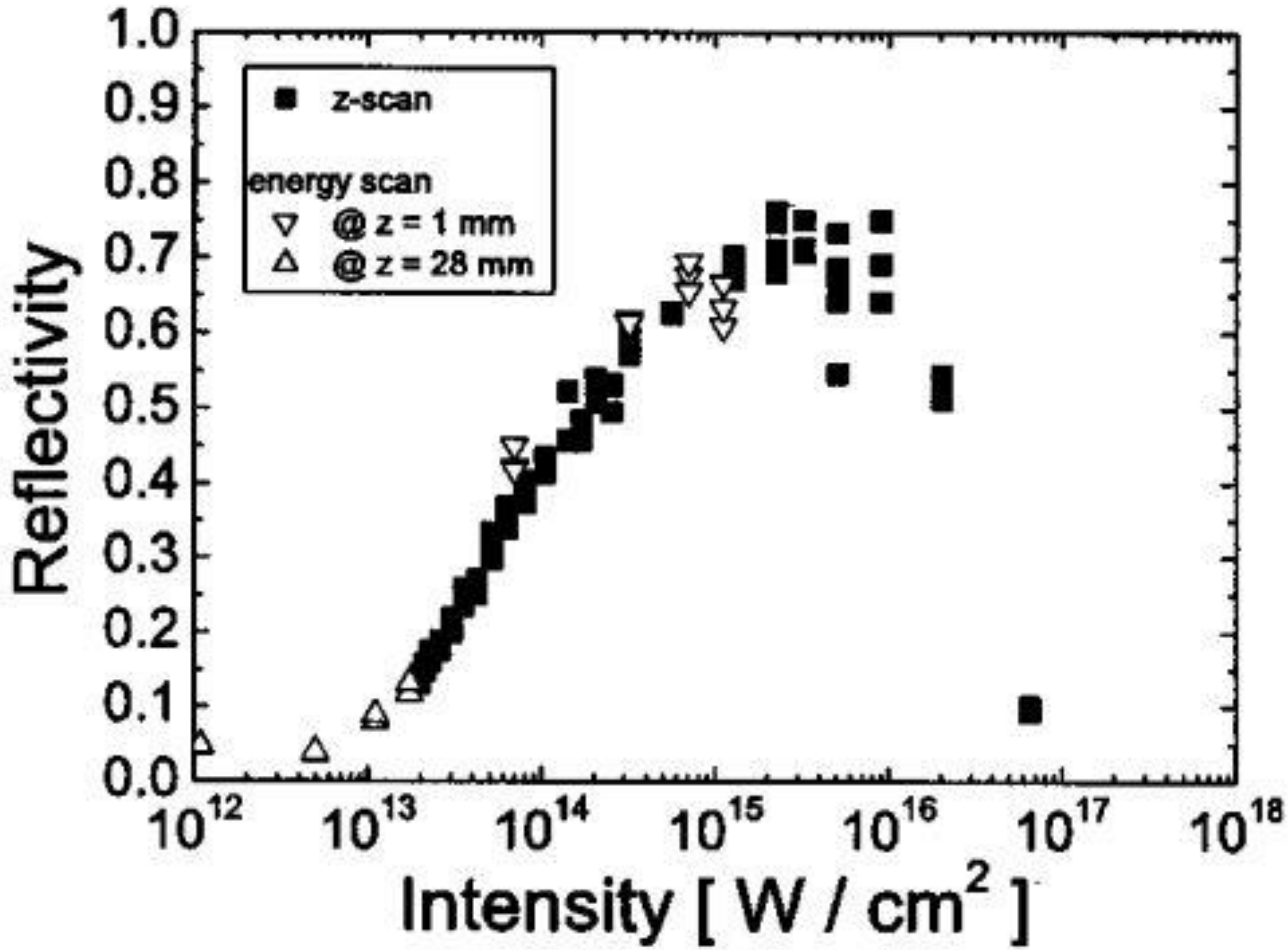
9.SHOW NON-CLASSICAL PROPERTIES

DEVELOPMENT OF HIGH INTENSITY SHORT PULSE LASERS IN TIME




Quantum, ultrafast, atomic-scale
Metasurfaces+ENZ
Metactronics
Metamaterials
Perfect lens
Term ‘plasmonics’ coined
Anomalous transmission through hole arrays
Nanoscale light guide
Near-field optical microscopy
First commercial SP biosensor
Observation of SERS
Plasmon excitation
with a prism
Plasmon
excitation
w electrons
we
Prediction
plasmons
Metamaterials
Number of articles
10000
1000
100
10
1
1950
1960
1970
1980
1990
2000
2010
2020
Year

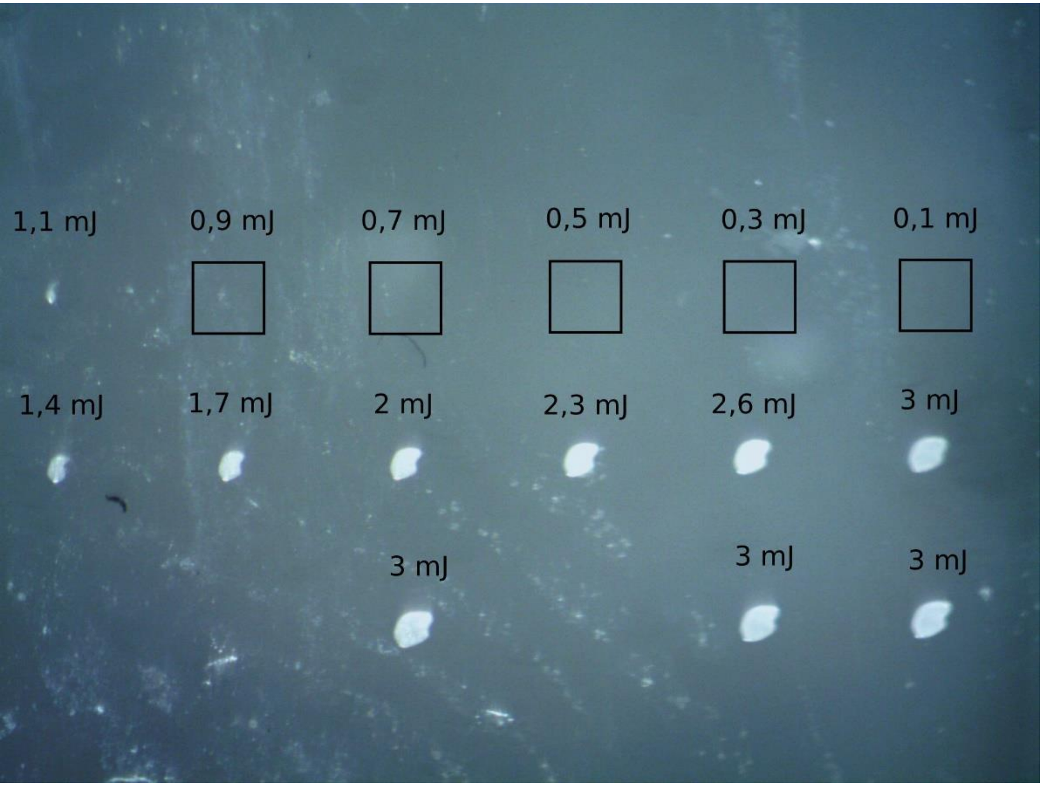
PLASMA MIRROR REFLECTIVITY



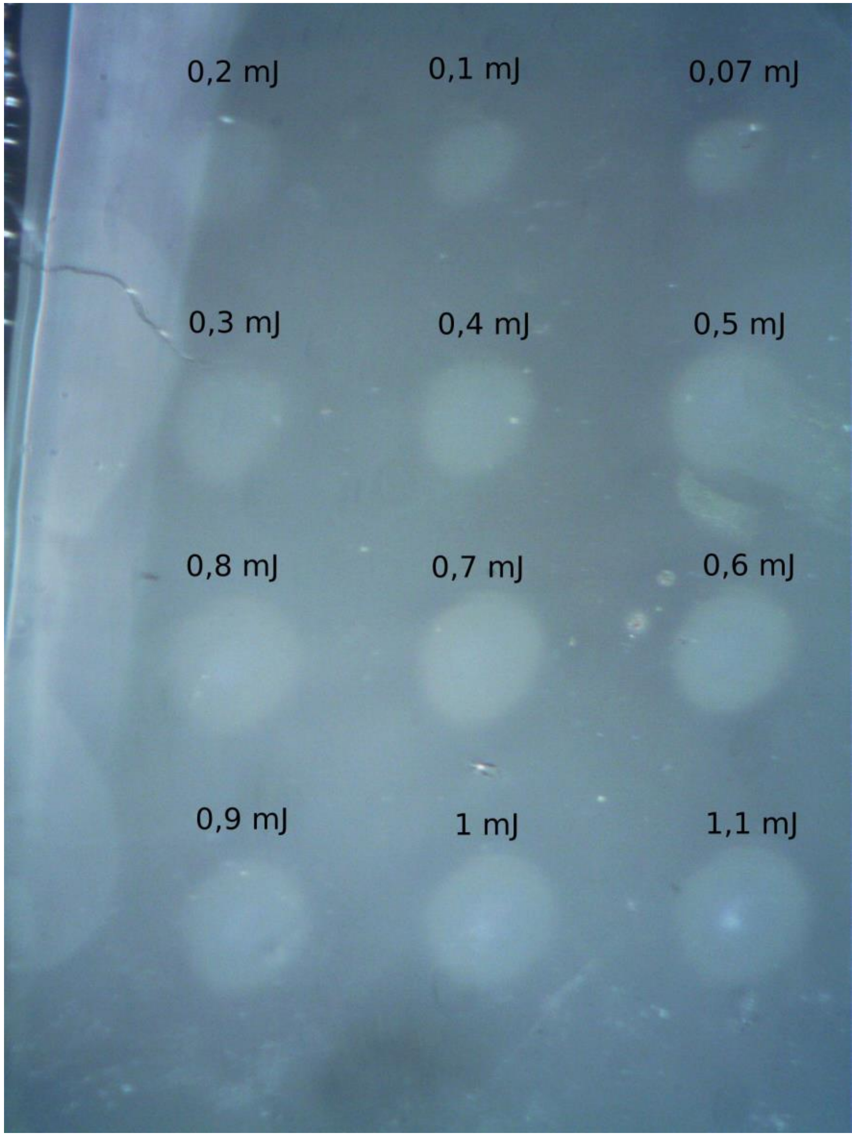
Ch.Ziener at al : J.Appl.Phys. 93,768 (2013)

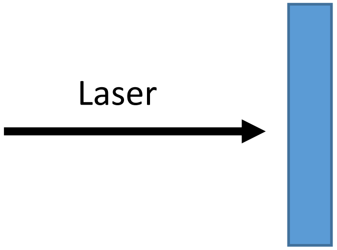
LIGHT NOT REFLECTED, GOLD NANOPARTICLES REACHED!

Non doped (amplification: 30x)



Doped (amplification: 40x)



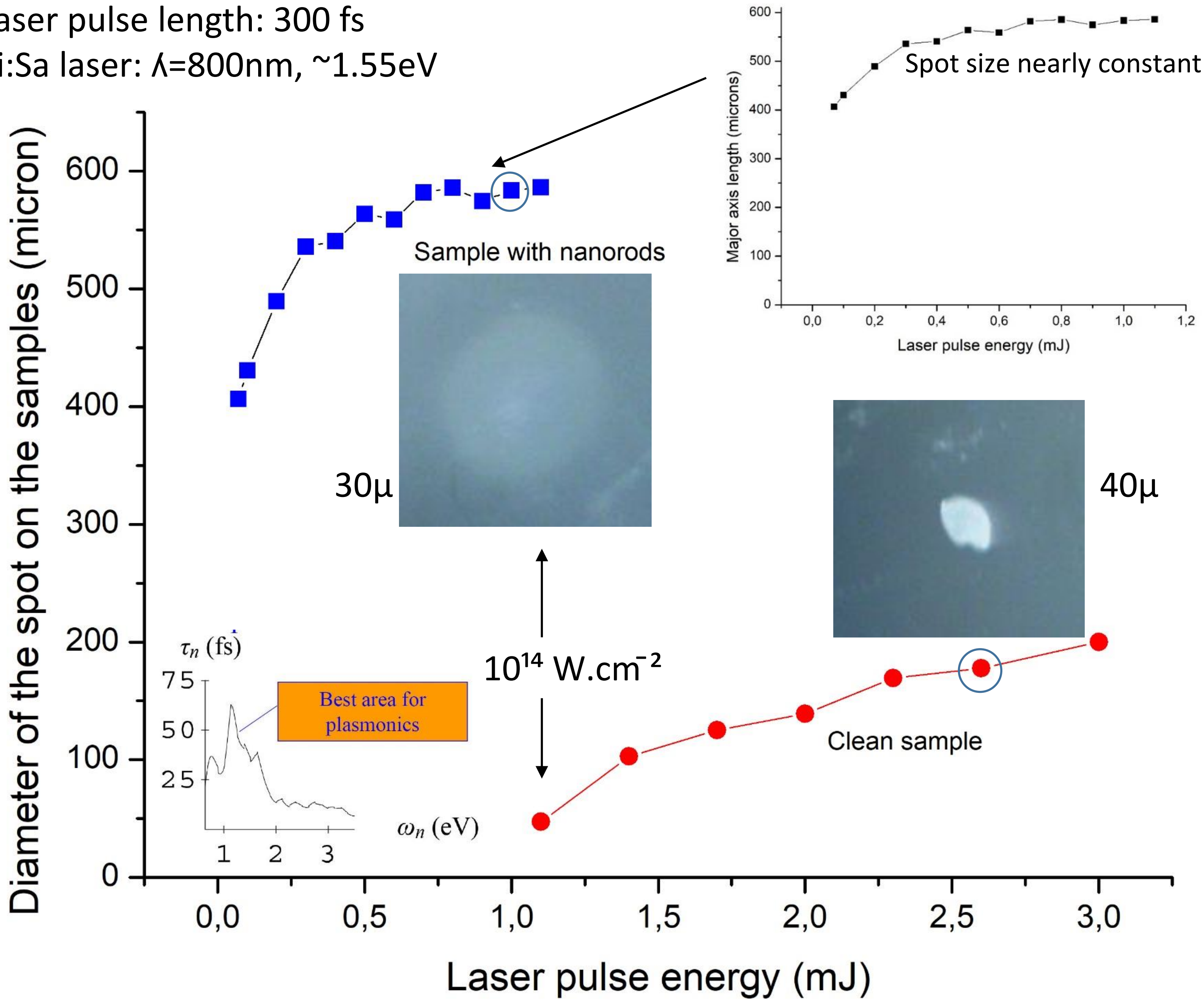


Focus: 20µ diameter
Pulse length: ~40fs
Intensity: max. ~4.10^{17}W/cm²

Thickness: ~30µ or 160µ

~10^{11}/cm³ gold nanoparticles

Laser pulse length: 300 fs
Ti:Sa laser: ʎ=800nm, ~1.55eV



Giant plasmonic amplification; the laserlight reaches the nanoantennas;

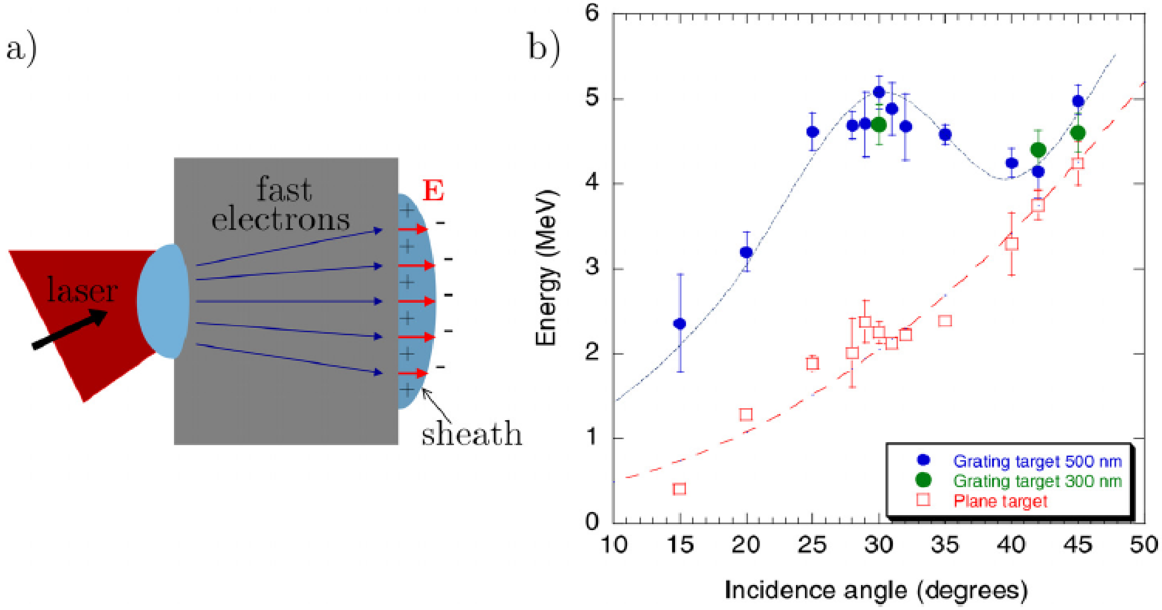


FIG. 5. Plasmon-enhanced TNSA of protons.[95] (a) Schematic of TNSA. The fast electrons produced by the interaction at the front side cross the target and produce a sheath at the rear side, where ions are accelerated. (b) Experimental data from the interactions of a high-contrast 25 fs, 2.5×10^{19} W cm^{-2} laser pulse with solid plastic targets. The cut-off energy of protons emitted from the rear measured as a function of the incidence angle from both flat and grating targets (for two different values of the grating depth). An up to 2.5-fold energy increase is observed for gratings, with a broad maximum around the resonant angle for SP excitation (30°). Data from Ref. 95.

Checcotti

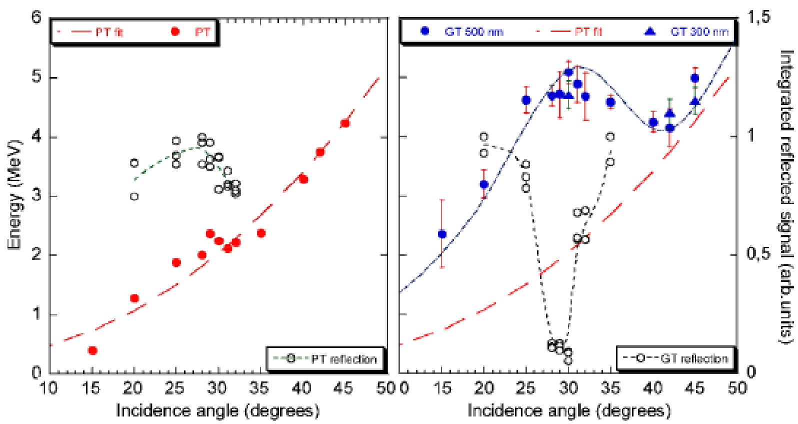


FIG. 3 (color online). Maximum proton energy (filled data points) and reflected light signal (empty data points) as a function of incidence angle α. Left and right frames correspond to 20 μm thick plane targets and to 23 μm thick grating targets, respectively. Filled circles and triangles correspond to 0.5 and 0.3 μm deep gratings, respectively. The (red) dashed line is proportional to $\sin^2\alpha/\cos\alpha$. The other lines are guides for the eye.

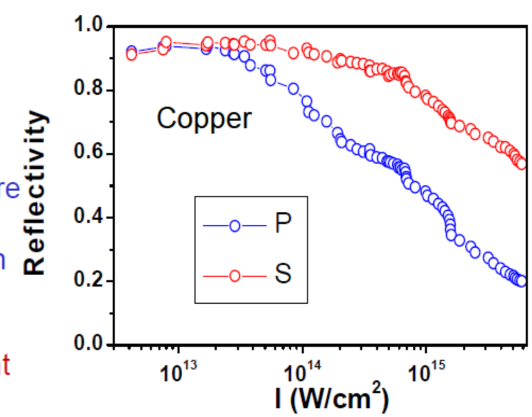
Plasma absorption

- A = 1-R

I < 3 x 10^{13} W cm^{-2}, A is almost polarization independent & obeys Fresnel laws, as IB is dominant

- at higher intensities, there is a clear polarization dependence of absorption

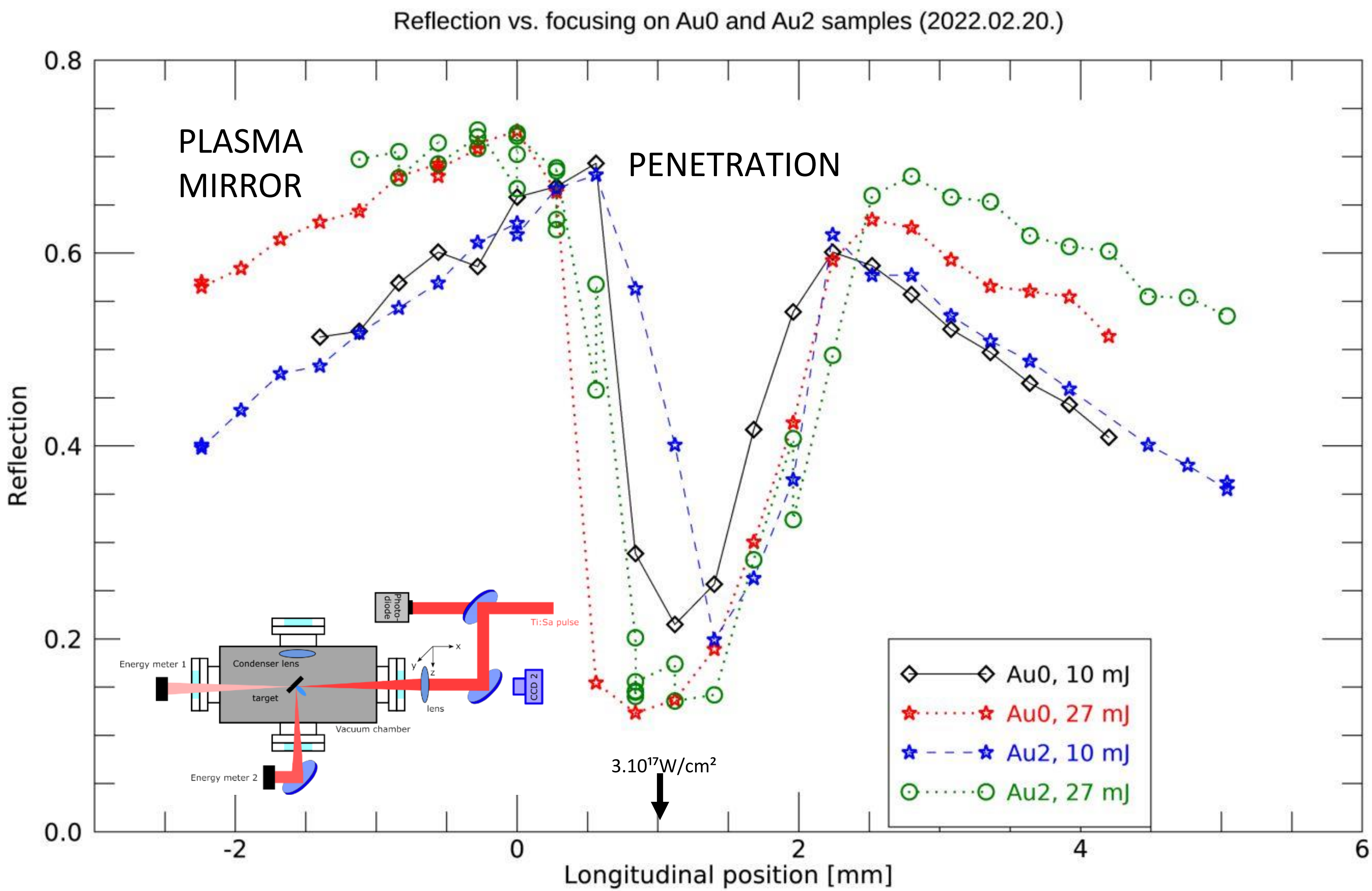
- the difference in absorption should account for extra absorption mechanisms, which are polarization dependent



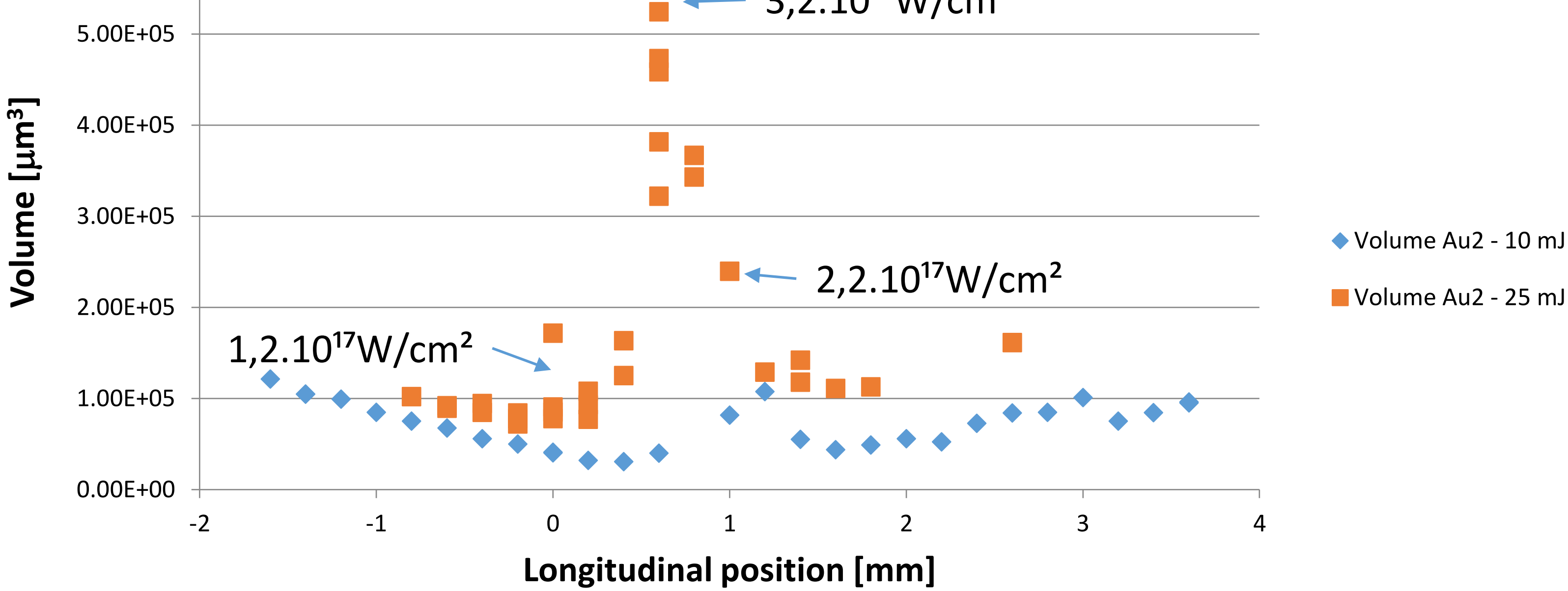
R vs I at 45°

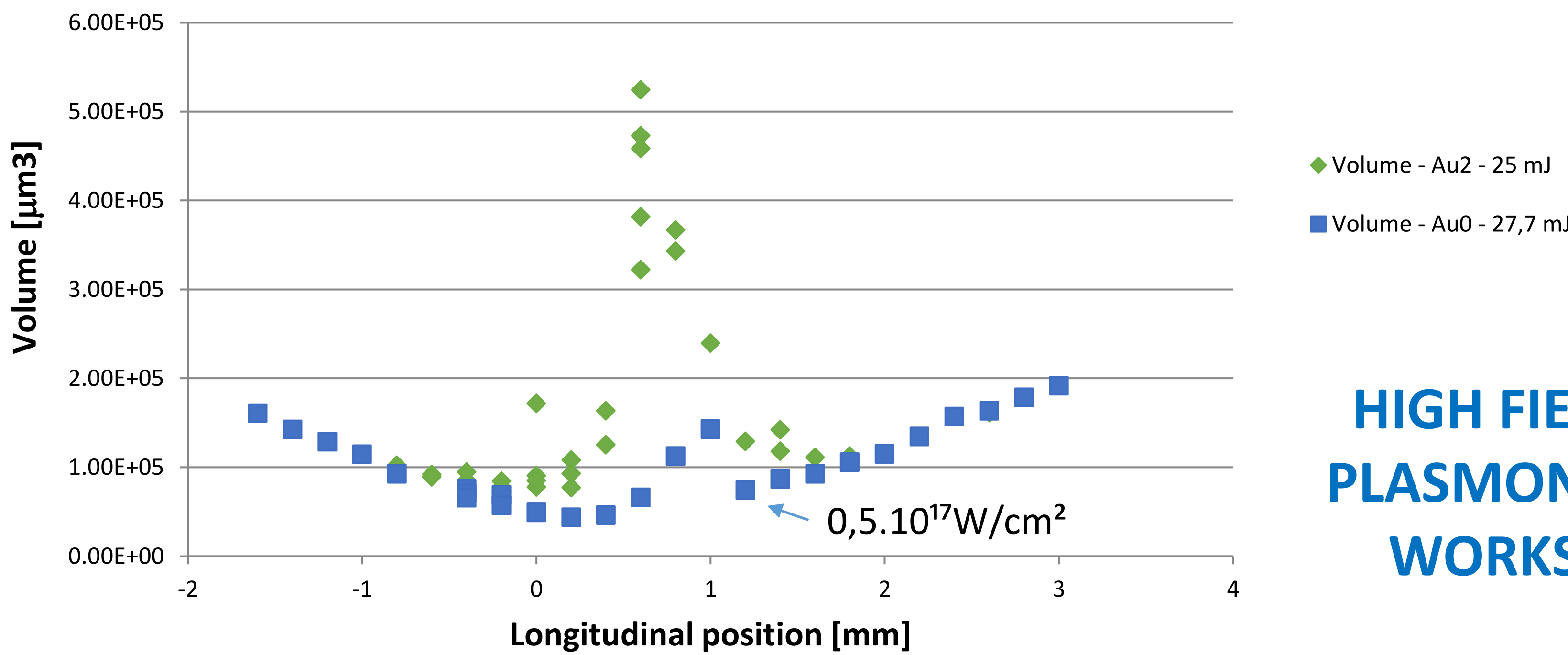
TIFR data

REFLECTIVITY OF A POLYMER FILM WITH AND WITHOUT RESONANT GOLD NANORODS

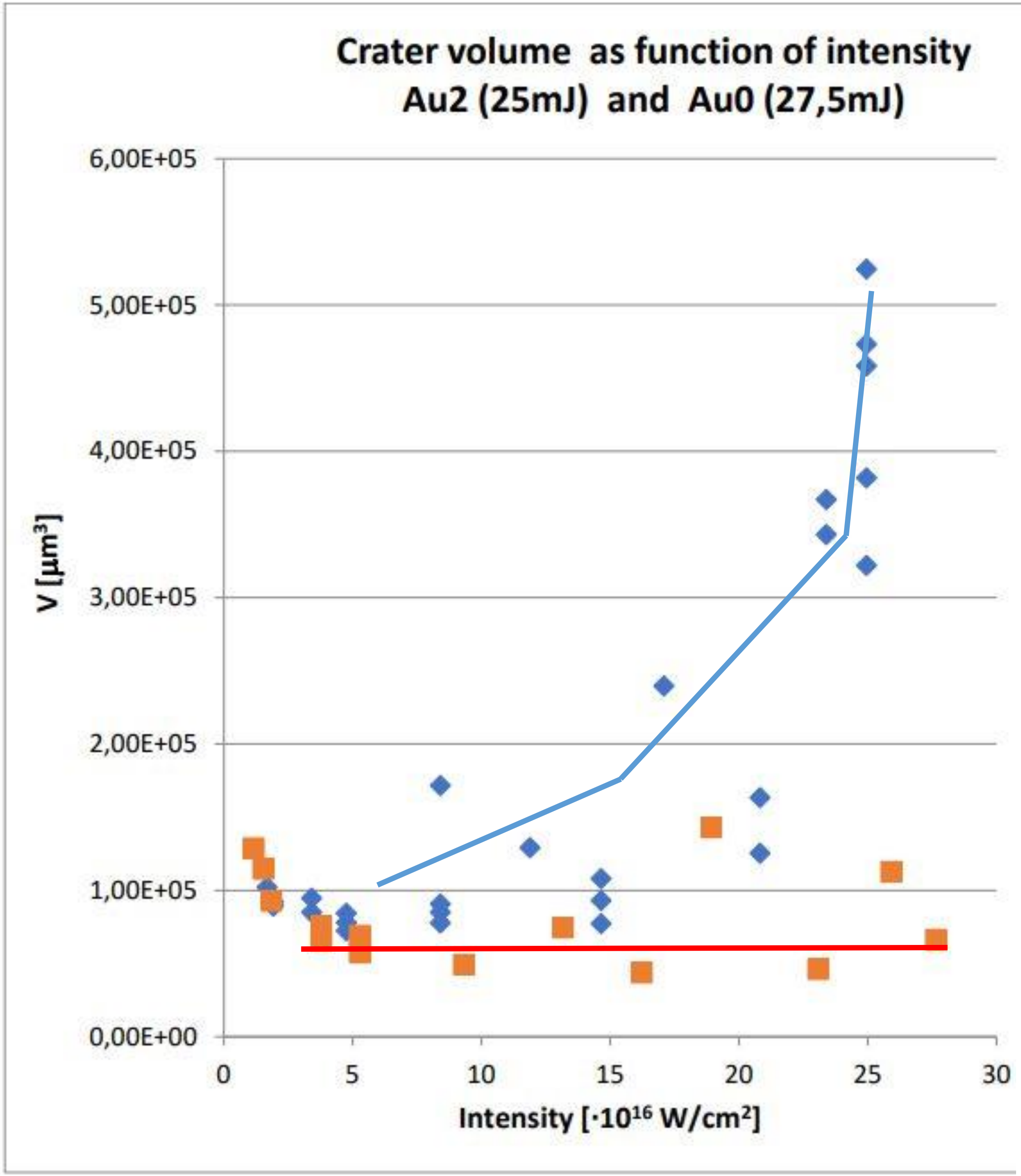


CRATER VOLUMES





HIGH FIELD PLASMONICS WORKS!



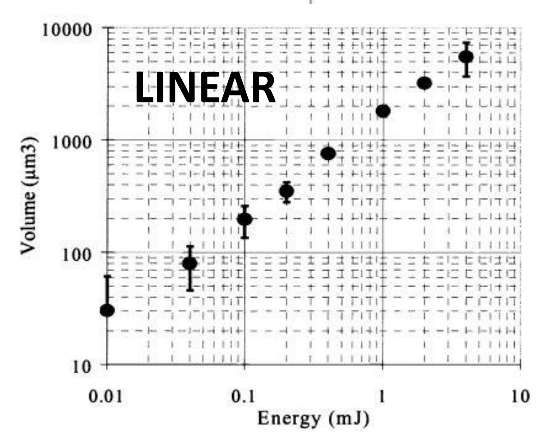


Fig. 4. Dependence of crater volume on laser energy for copper. (532 nm, 6 ns)

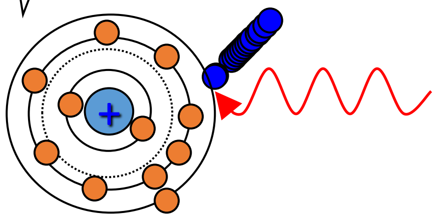
No1 appl.

Matter under extreme conditions

(extremely high intensities)

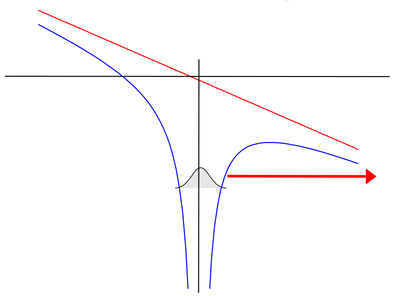
single atom

$I = 10^{16}$ W cm^{-2} → E ~ 10^9 V/cm

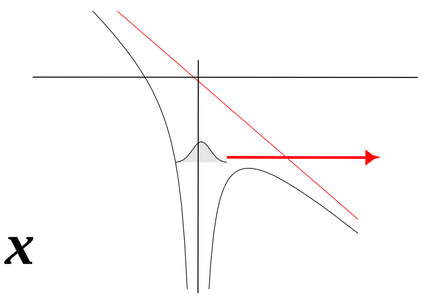


High intensity
Photoeletric Effect

Rapid ionization of valence electrons



$$V = -\frac{q}{x} \pm E.x$$



Tunnelling

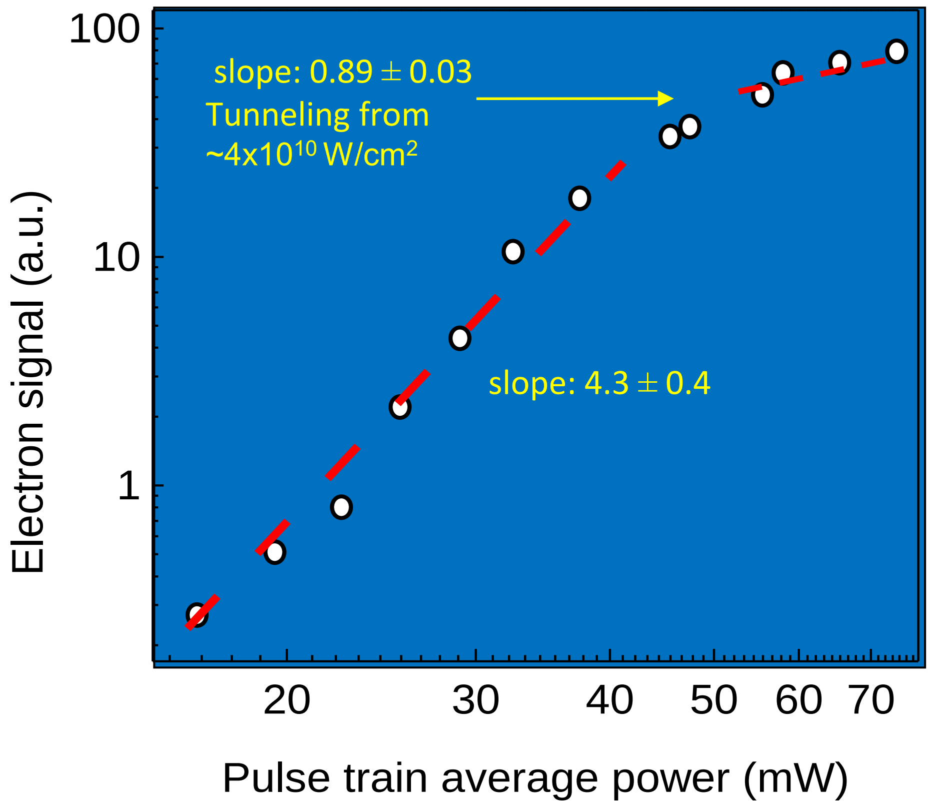
10^{14} - 10^{15} W cm^{-2}

Over the barrier

> 10^{15} W cm^{-2}

Each atom loses at least one electron. Some can lose as many as 6 !

MULTIPHOTON ELECTRON EMISSION FROM GOLD



Multiphoton → tunneling transition at ~4x10^{10} W/cm^2 incident intensity, ~5.5x10^8 V/m field

Keldysh-gamma γ=31

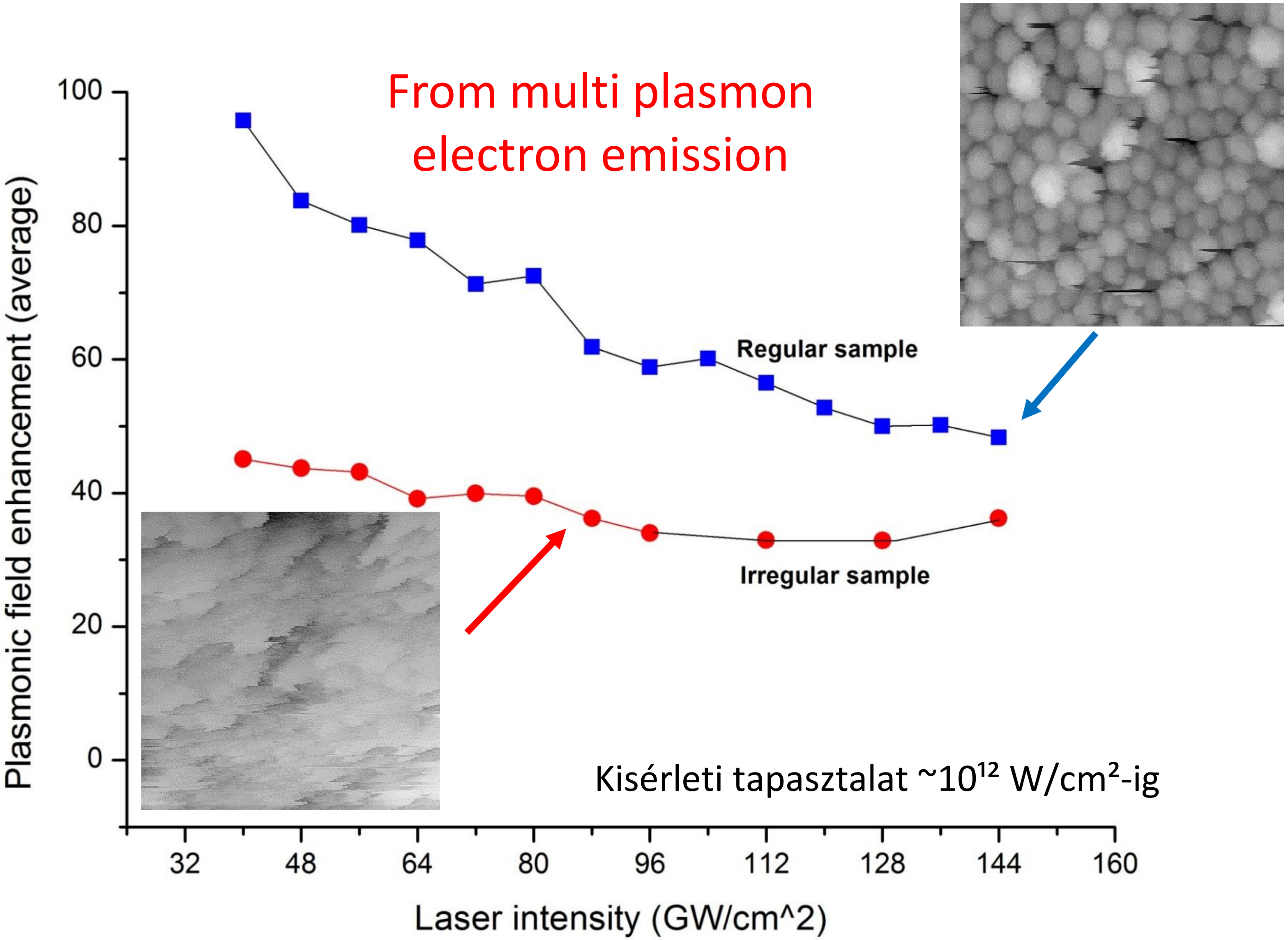
→ indication of well-known field enhancement of surface plasmonic fields

$$\gamma^2 = \frac{W}{2U_p} = \left(\frac{\omega\sqrt{2mW}}{eE_l} \right)^2$$

W: work function, E_l: laser field strength

PLASMONIC ENHANCEMENT!

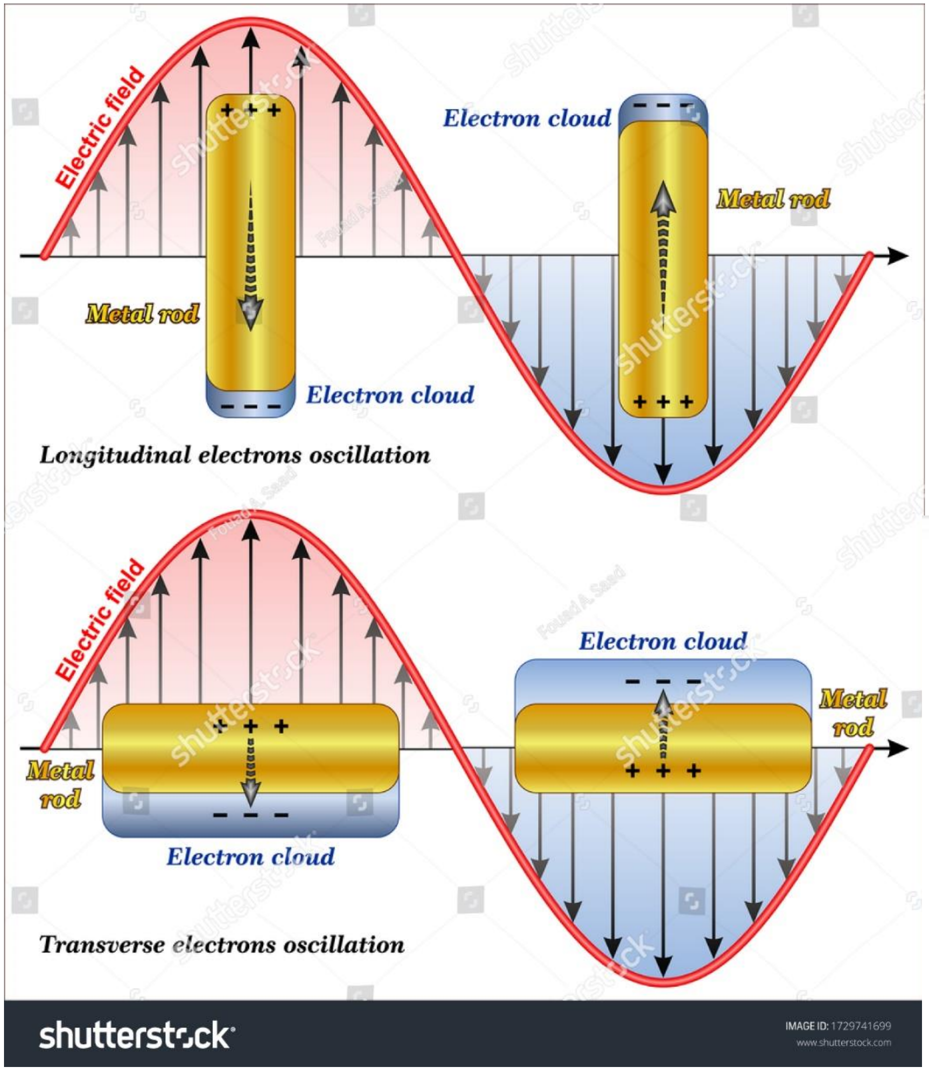
From multi plasmon electron emission

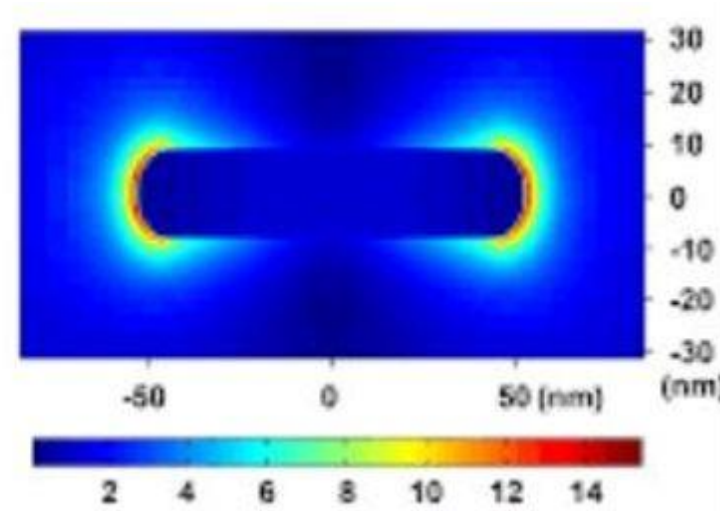


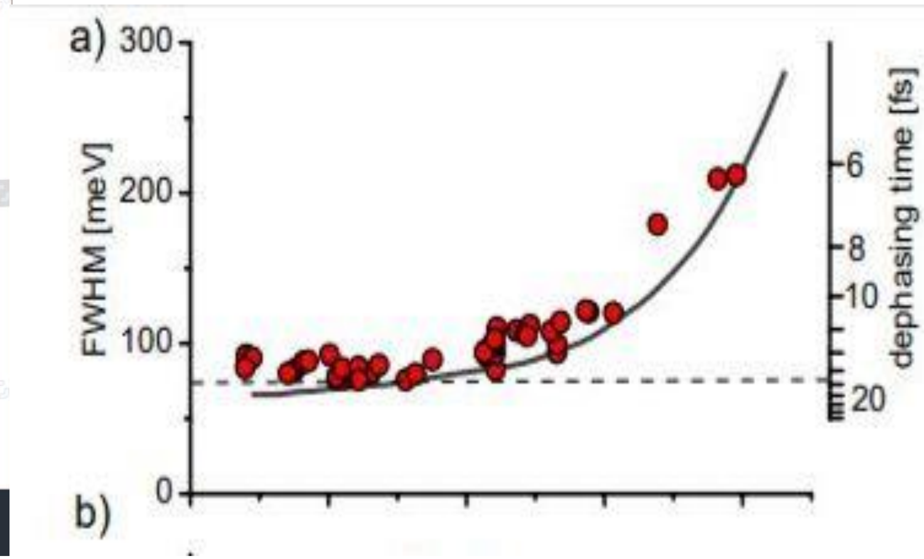
Born-Openheimer?: >10^{15} W/cm²; Relativistic phenomena: >10^{18}W/cm²

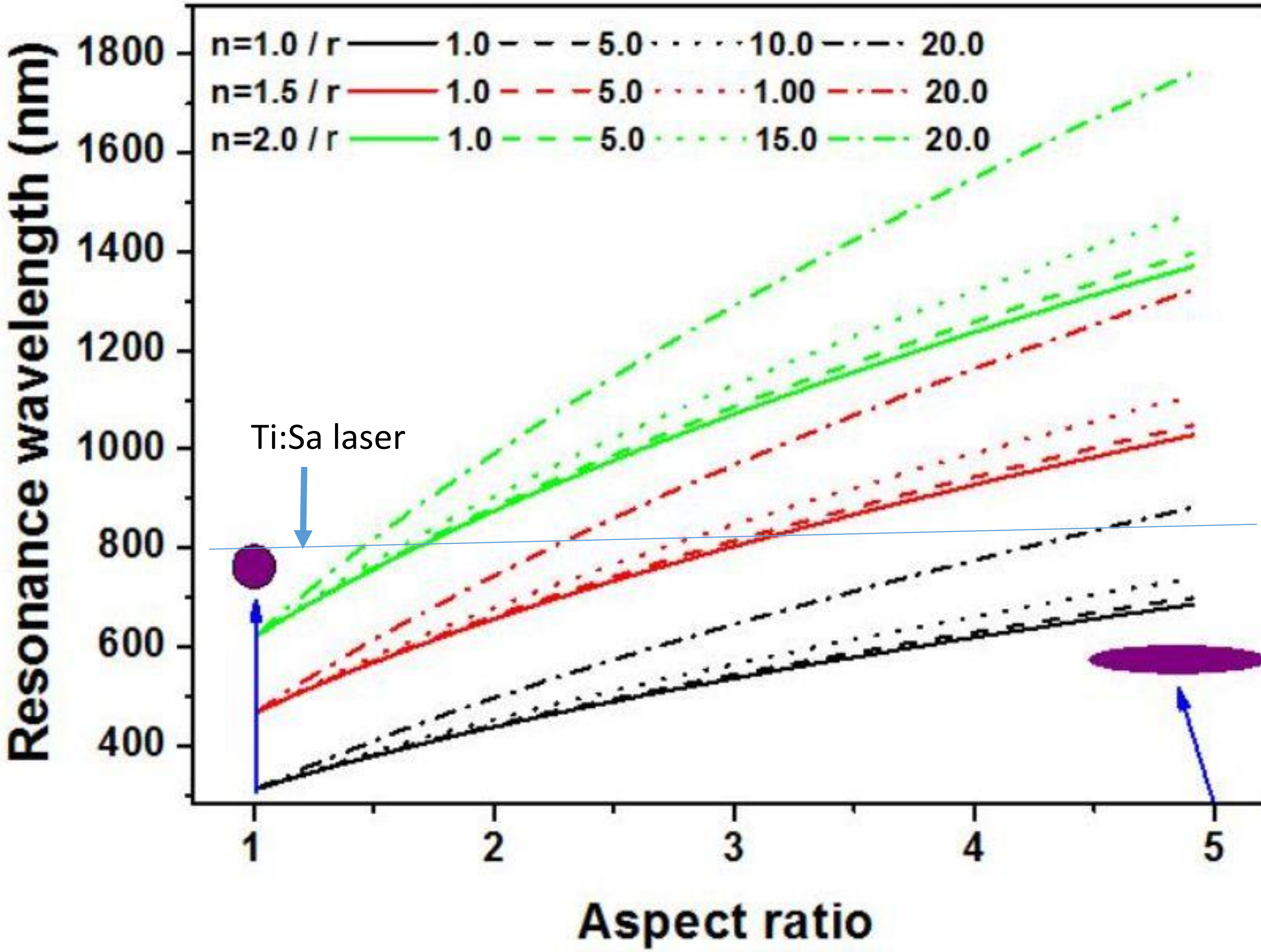
MAY PLASMONS EXIST IN THESE LASER INTENSITY REGION?

Transverse and longitudinal modes!








n=1.0 / r 1.0 5.0 10.0 20.0
n=1.5 / r 1.0 5.0 1.00 20.0
n=2.0 / r 1.0 5.0 15.0 20.0
Ti:Sa laser
Resonance wavelength (nm)
1800
1600
1400
1200
1000
800
600
400
1
2
3
4
5
Aspect ratio

Ti:Sa LASER SPECTRA AT DIFFERENT PULSE ENERGIES

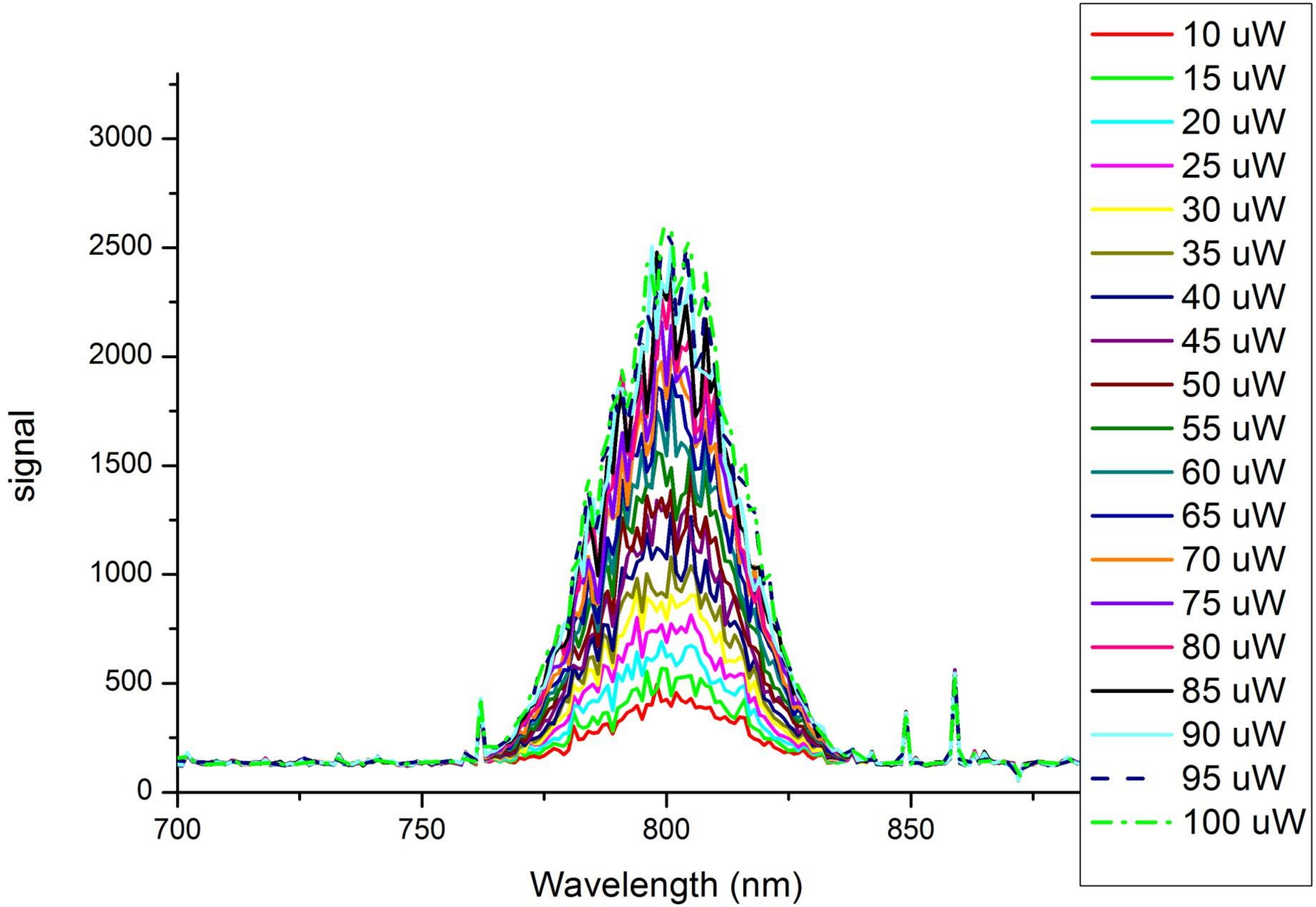
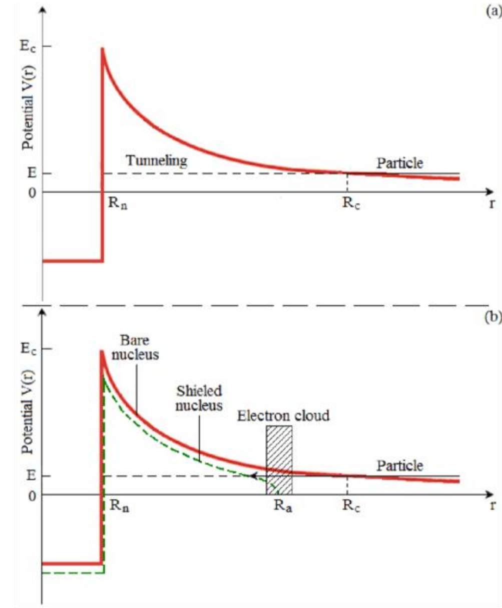
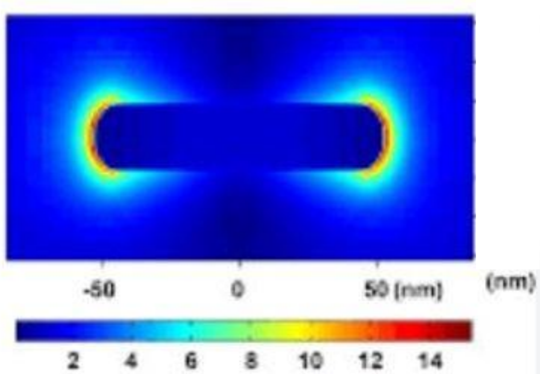


ILLUSTRATION OF THE RESULT OF THE SCREENING EFFECT





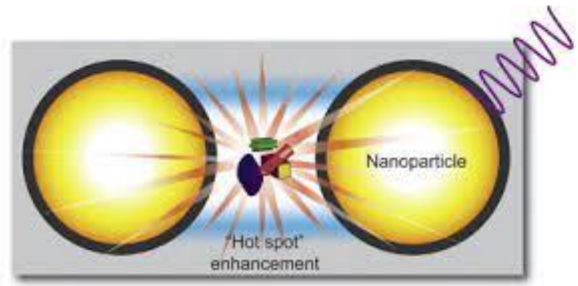
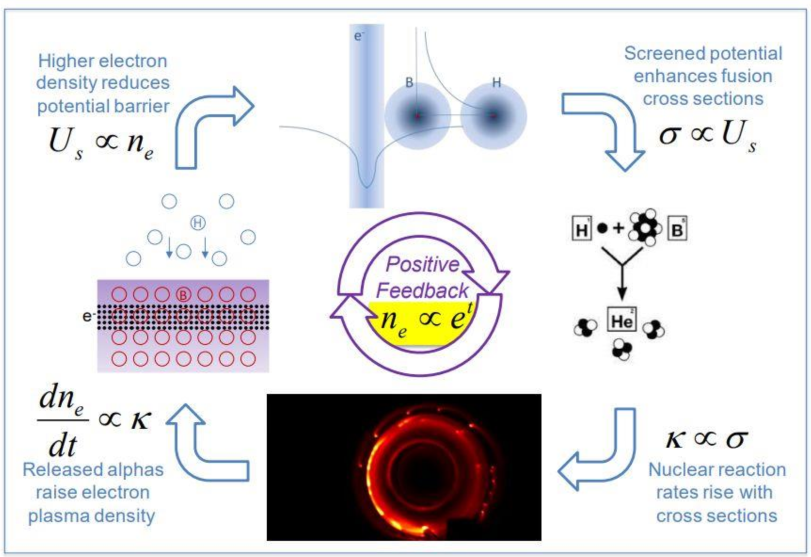


Illustration with the H+B ⟶ 3He reaction

Ponderomotive screening

$F_p = (e^2/4m_e\omega^2).\text{grad}\,(E^2)$



A.Y.Wong and C-C.Shinh:UCLA 2019

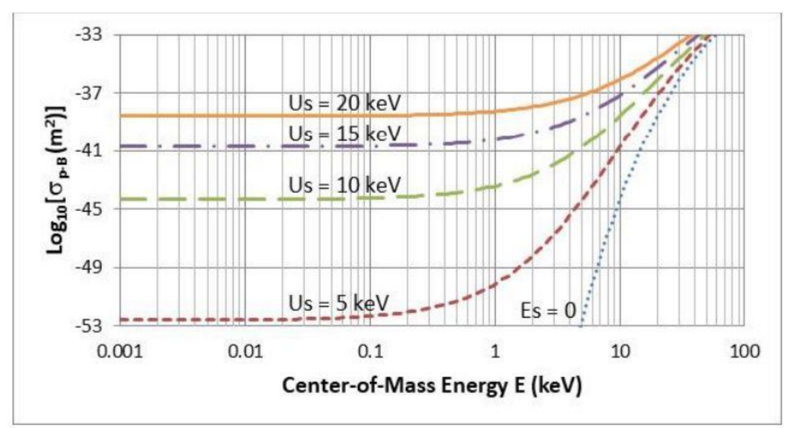
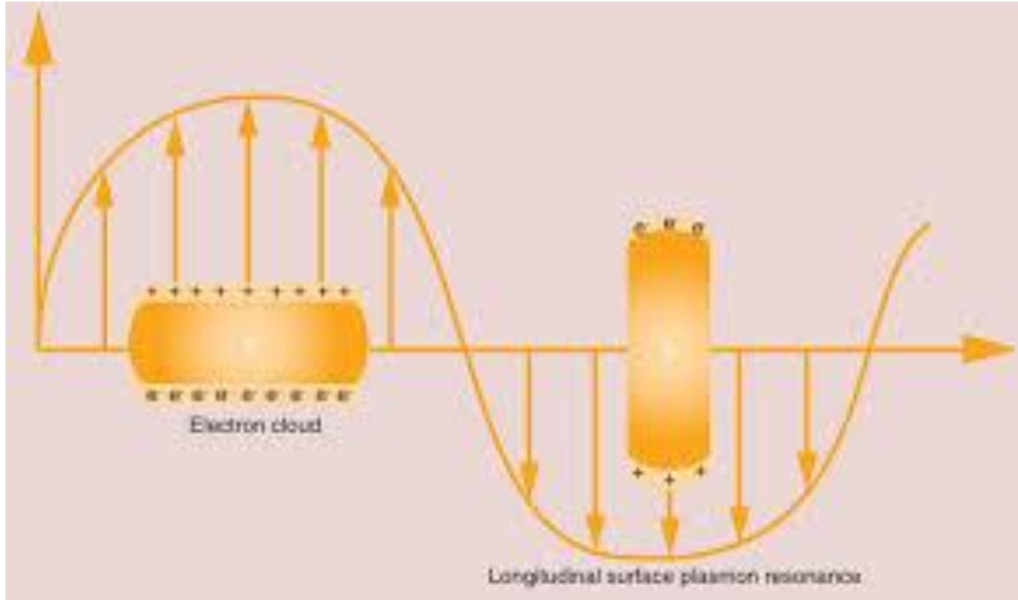
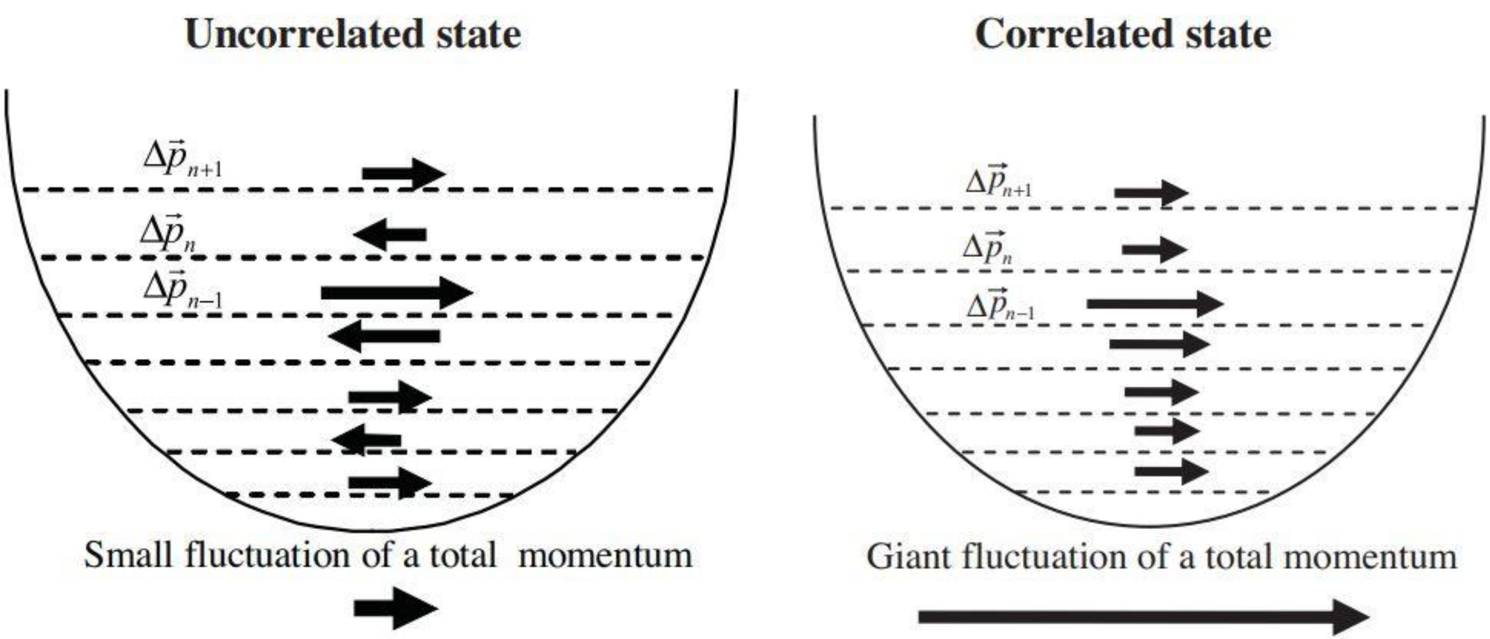


Figure 1: p-^{11}B cross section as function of particle energy for the screening electron densities up to E_s = 20keV. The cross section near E = 10eV grows over 14 orders of magnitude (from 10^{-53} to 10^{-39}m^2) over the range of 5 to 20keV.

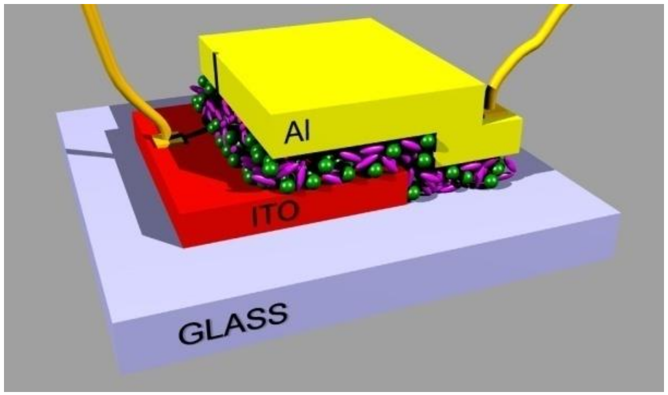
Demonstration of the correlated state

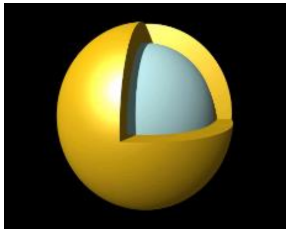


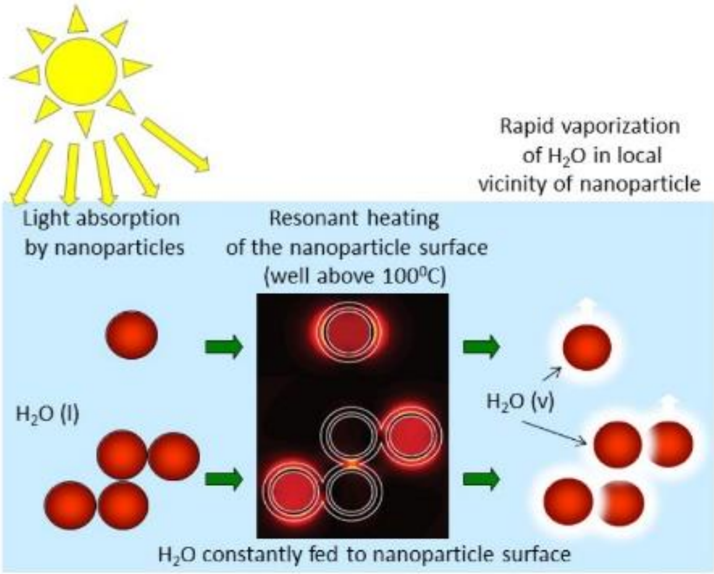


Some potential new energy technologies

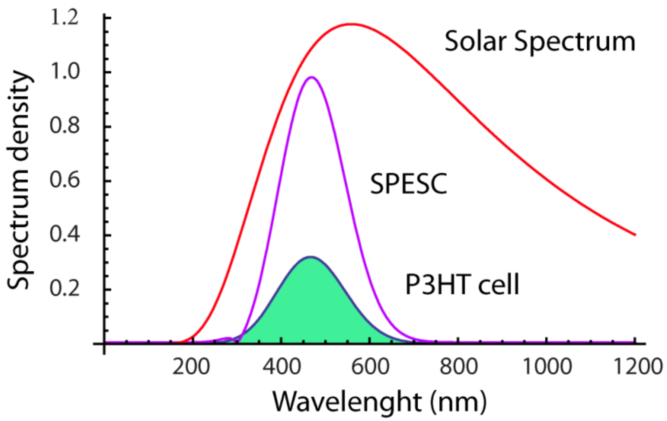
(involving nanotechnologies)

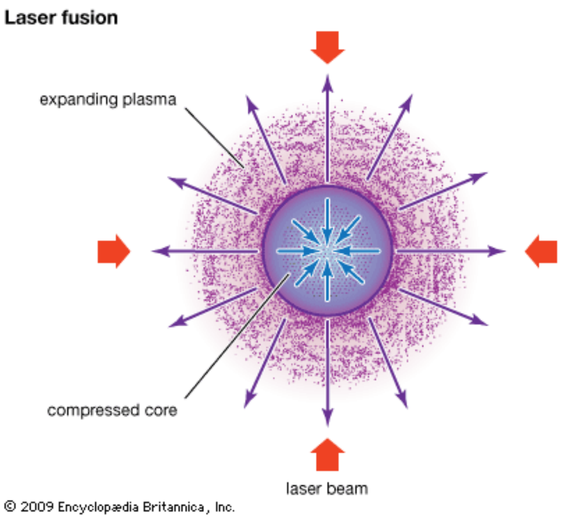


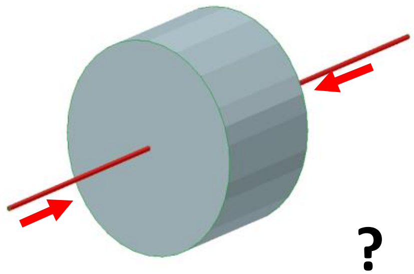




P3HT Cell efficiency = 6%
SPESC (P3HT) efficiency = 17.5%

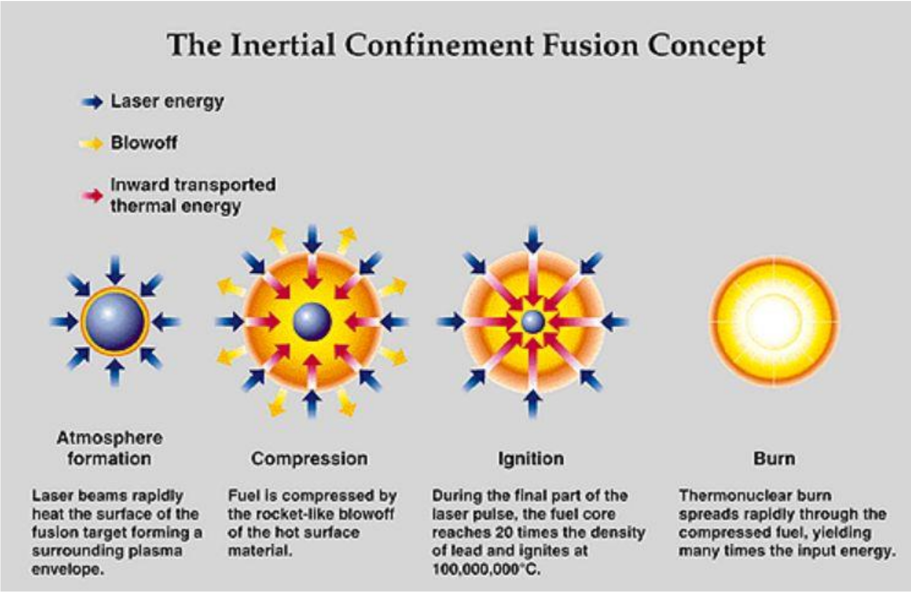






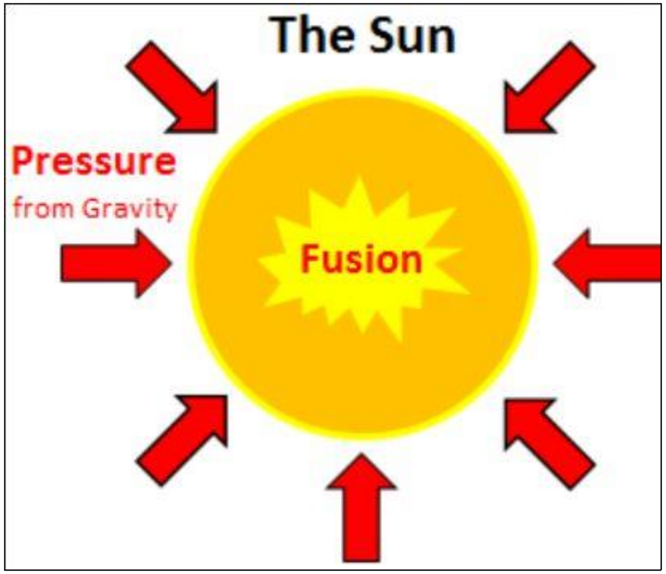
Toward our proposal

No2 application (LSPP)

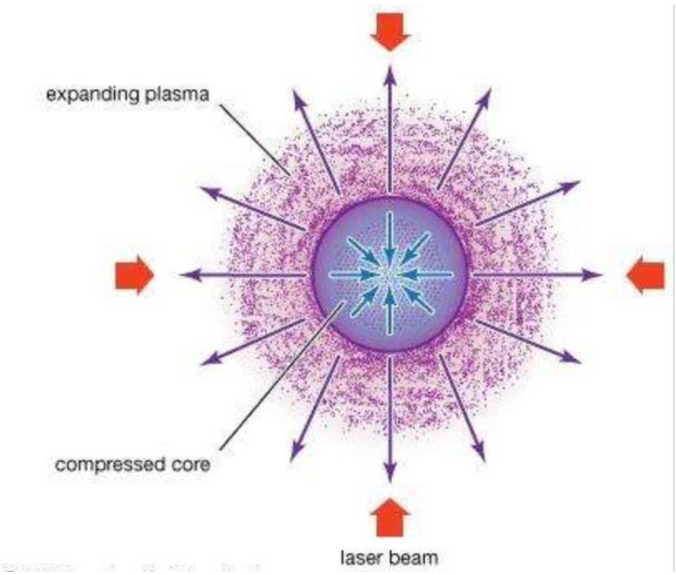


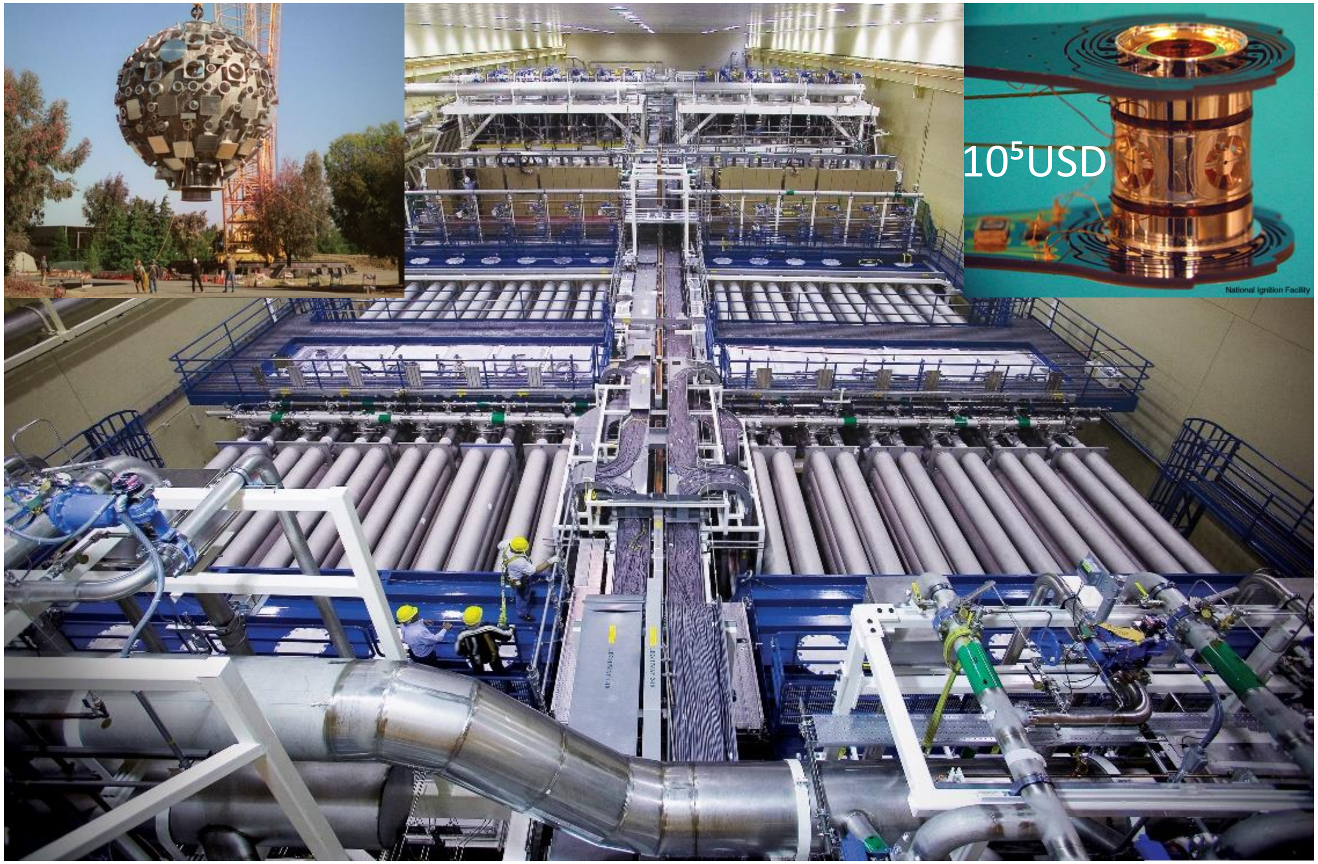
The most succesful technologies imitate nature

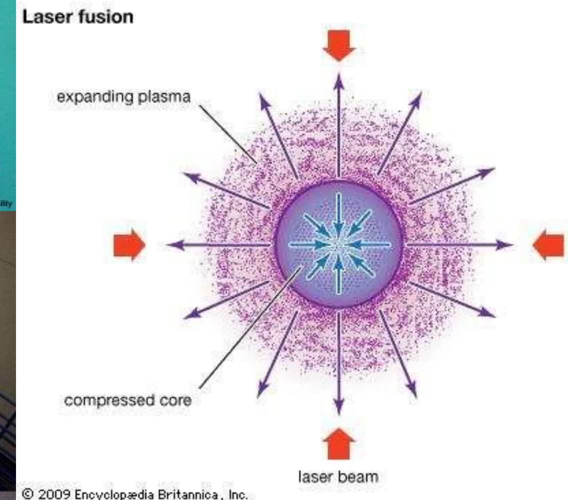
$E = mc^2$



Laserbeams







Long laser pulses (~50ns)
Raileigh-Taylor instability
Complicated target construction
Enormous laser energy (400/1.8MJ)

Problems of inertial fusion

- High requirements on irradiation symmetry
- Insufficient laser repetition rate
- Very precise injection system is needed
- The target position has to be tracked in order to ensure required irradiation precition

TO COMBINE 2 DIFFERENT (e.g. fusion and nano-) TECHNOLOGIES TO REACH FUSION AT THESE ULTRAHIGH EM FIELDS?

OUR PROPOSAL: COMBINE PLASMONICS WITH NUCLEAR FUSION TECHNOLOGY

SOME POTENTIAL EXPLOITABLE HIGH FIELD PLASMONIC PROCESSES:

1. Go for localized surface plasmon polaritons (LSPP)

2. Lifetime of LSPP-s is in the few ten femtosecond timerange. We may get high intensity laser pulses in this timediapazon and the plasma instabilities disappear.

3. High electron densities and EM fields can be obtained in small (nanosized) volumes on resonant plasmonic nanoparticles (hot spots).

4. The near field of plasmons screen the repulsive field of positively charged (e.g. protons) particles and they may fuse more easily.

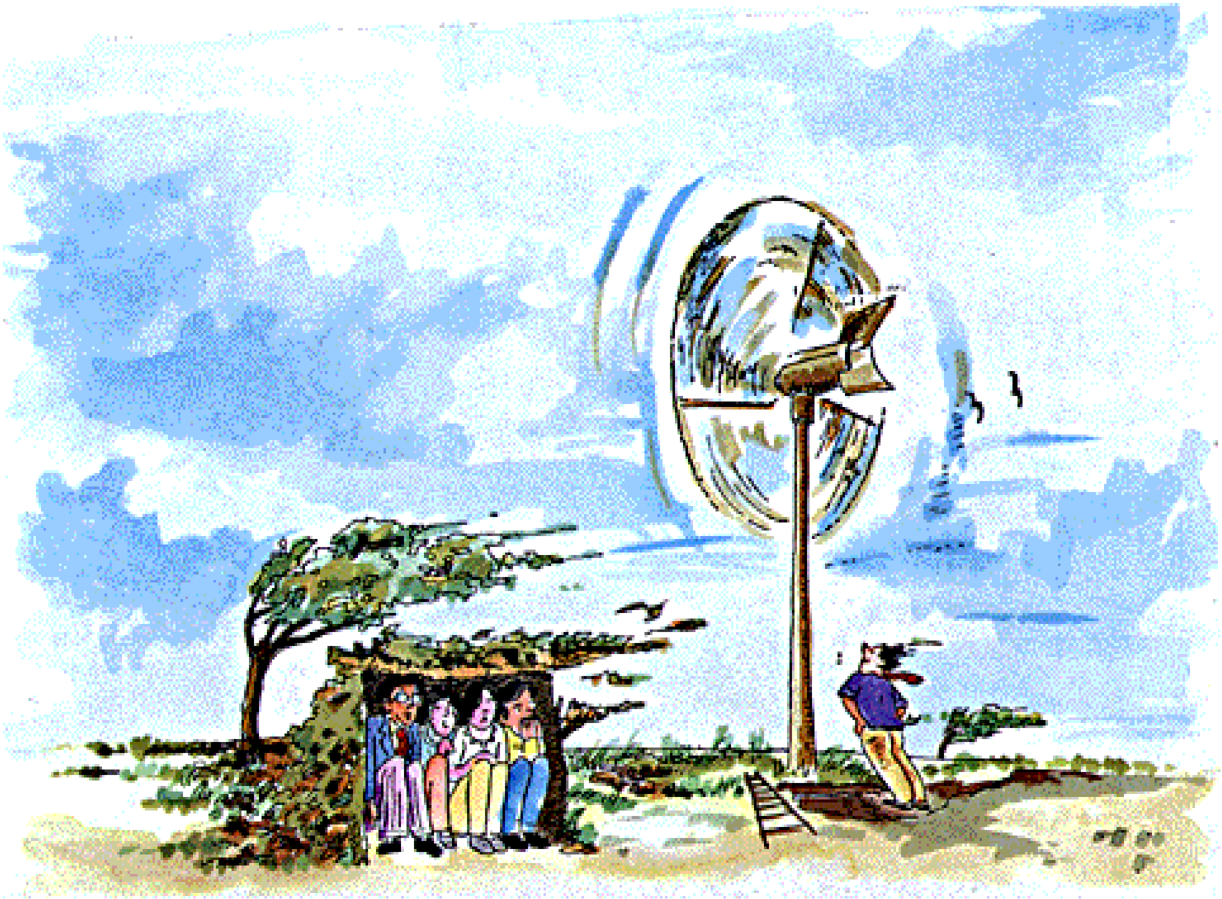
5. The large number of conduction electrons move in plasmonic excitations in correlated way and their momentum may be transfered in high exciting fields to positive particles moving together with them, further increasing the probability of nuclear fusion.

6. With these short pulses we do not need many beams, like in the NIF, the target can be a thin film, illuminated only by 2 beams from opposite directions, reaching the same energy density in the whole thicknes of the target sample, and this may lead to timelike fusion.

OUR GOAL IS:

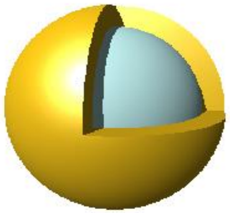
To explore these properties of LSPP-s with the intention to

- drive for nanoplasmonic aneutronic fusion reactions,
- and this way scale down the size and costs of laser based nuclear fusion facilities;
- find solutions at lower optimal laser intensities;

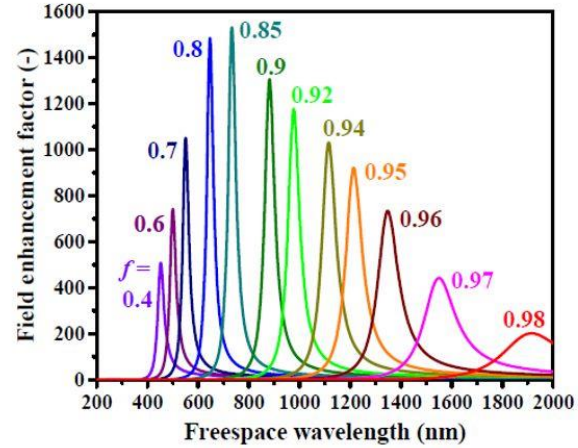


When the winds of changes are blowing some build shelters, but some others build wind turbines

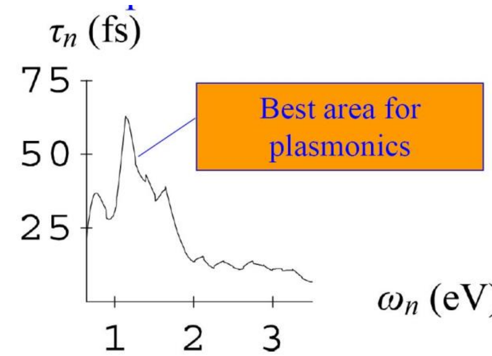
Resonant



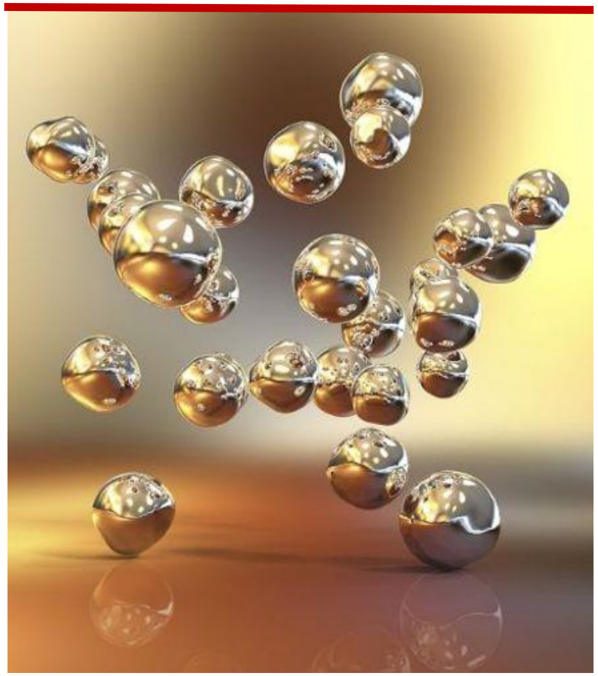
NANOSHELLS (nx10nm)

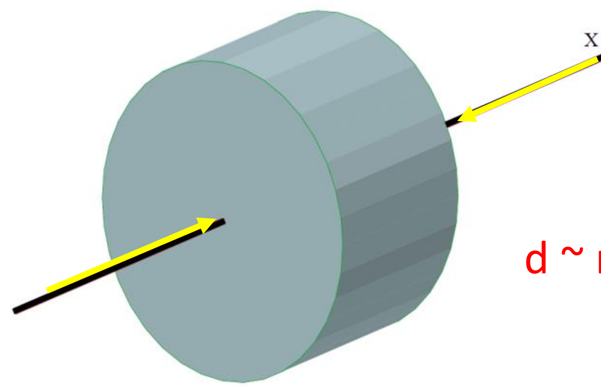


Λ = 800nm



NANOROD (~85x25nm)





d ~ n.10µ

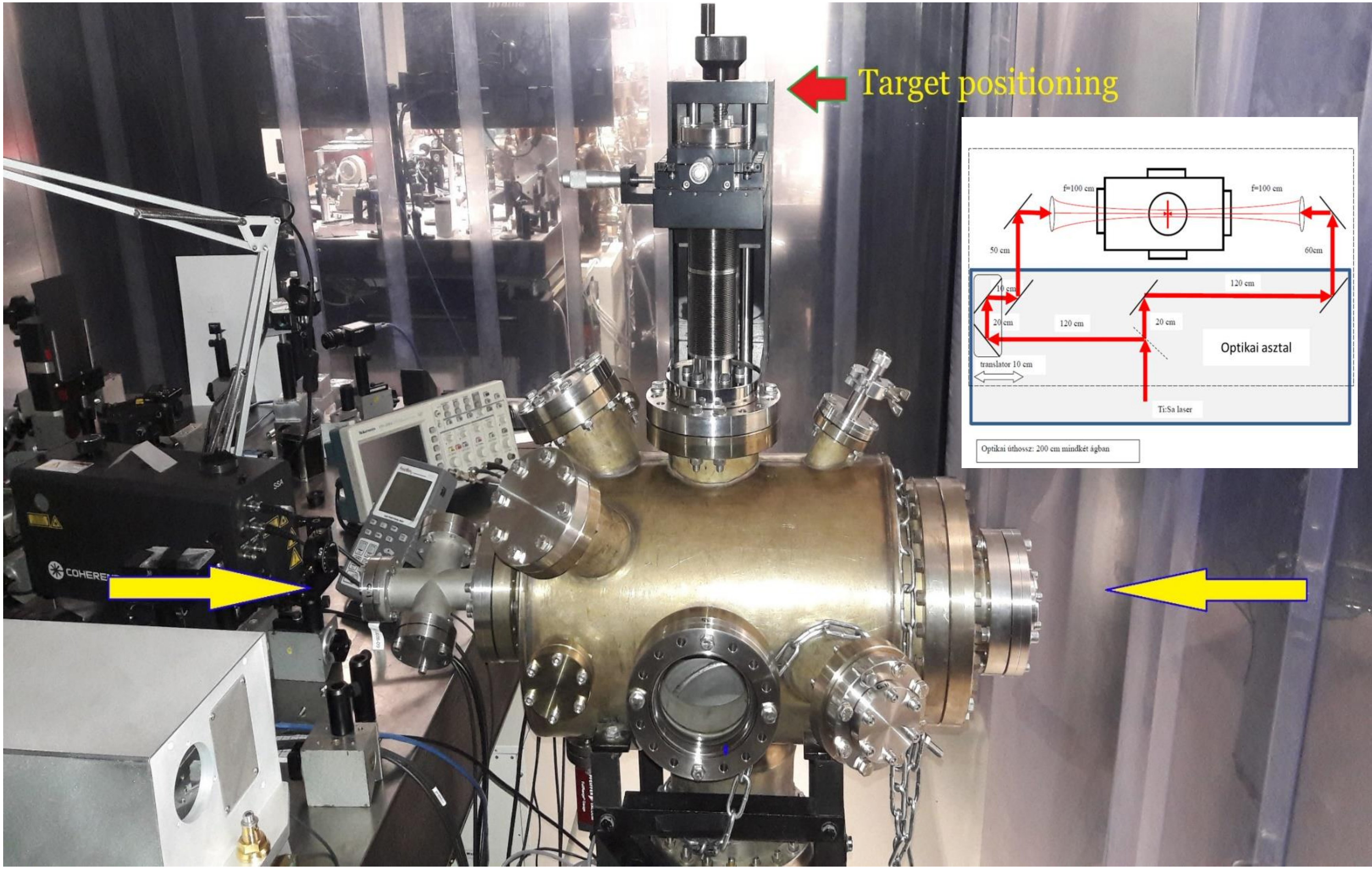
n.10µ

NANOPARTICLES IN THE FUSION MATERIAL

FEMTOSECOND LASER PULSES
HIGH REPETITION FREQUENCY
LIGHT SPEED: NO TIME FOR INSTABILITIES,ONLY TWO BEAMS, VOLUME IGNITION

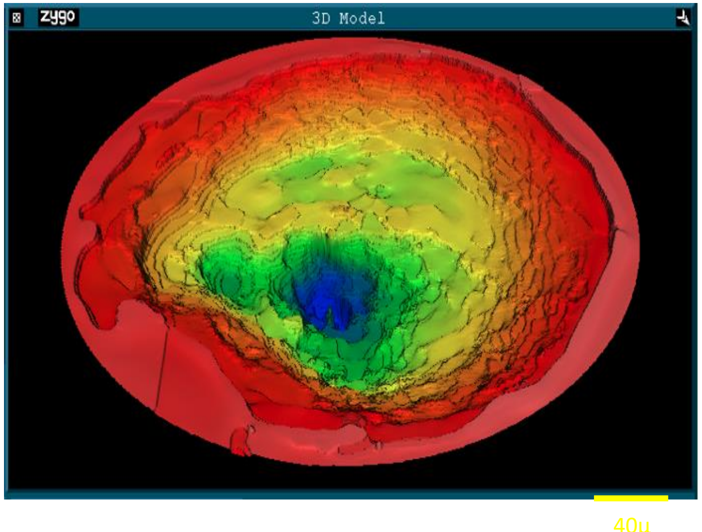
Here only indications. Details in other talks, both in theory and experiments.

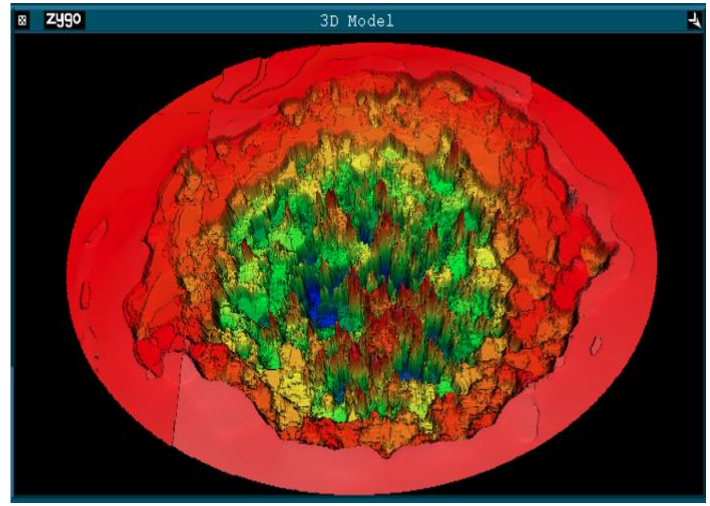
Two-sided irradiation



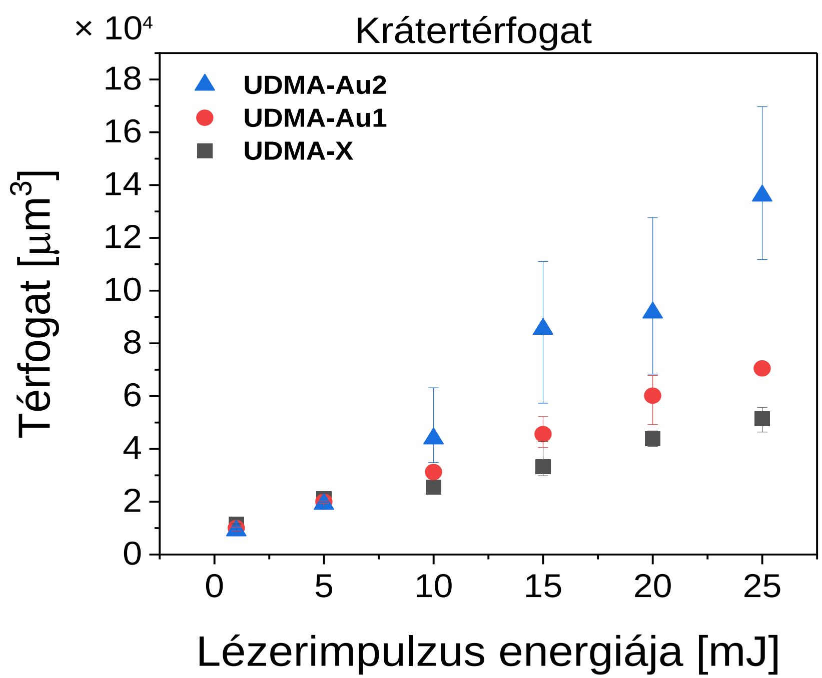
1. DIAGNOZIS (crater volume)

Volume: V_0

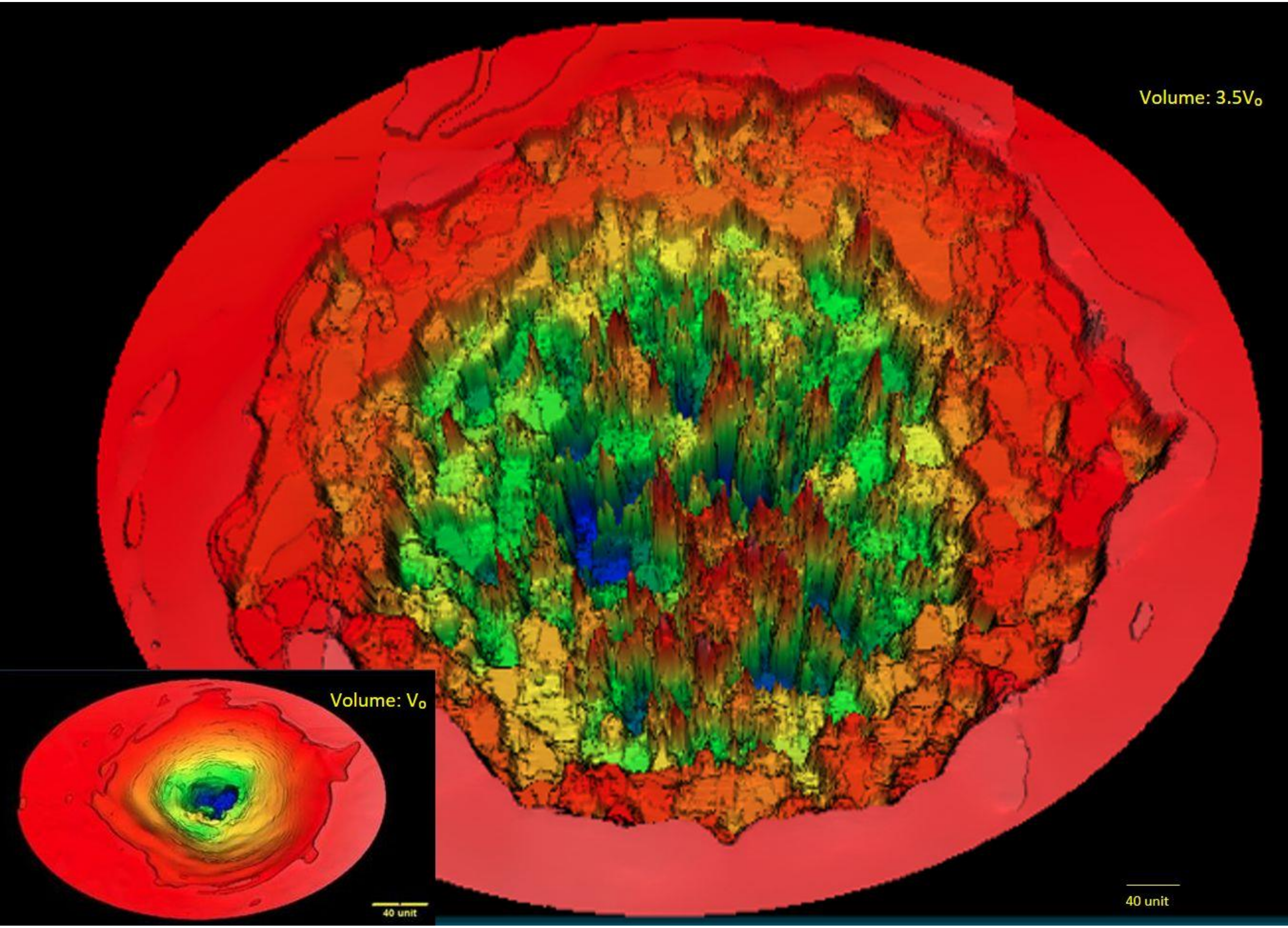




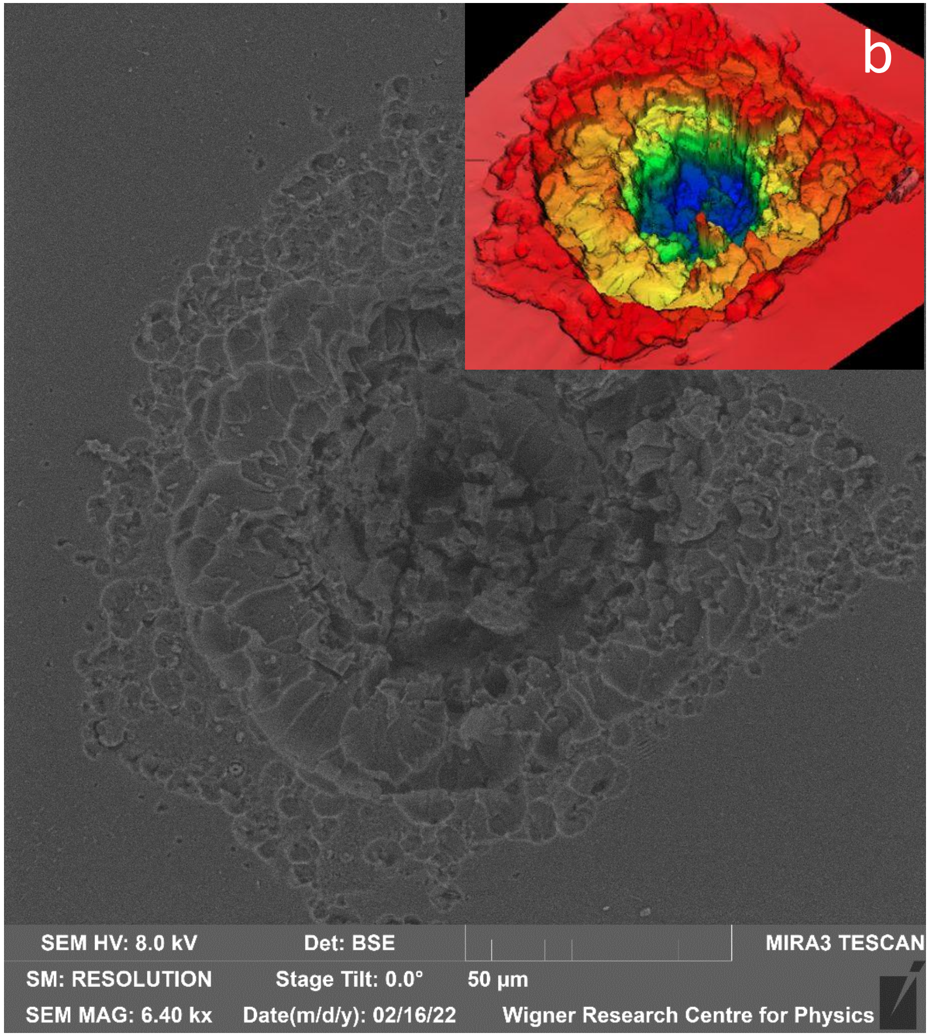
Volume
max. $3.5V_0$

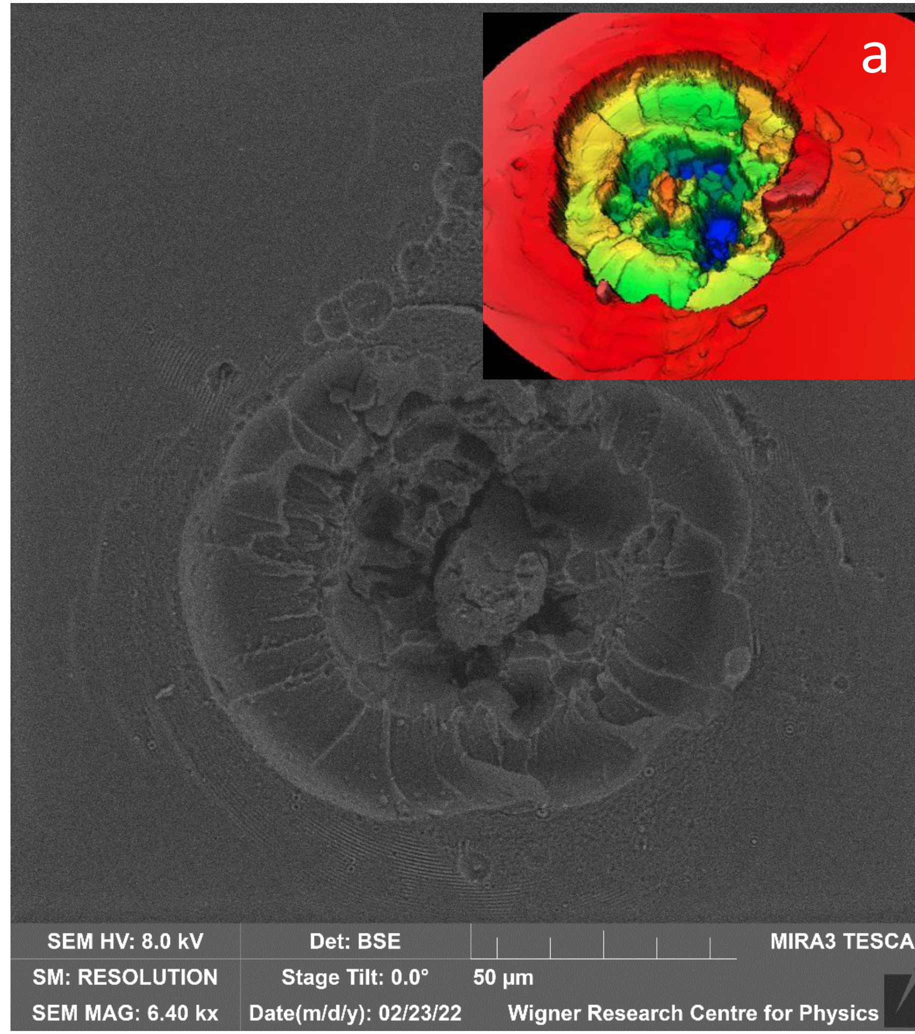


Laser shots from one side of a thick (~160µ) foil

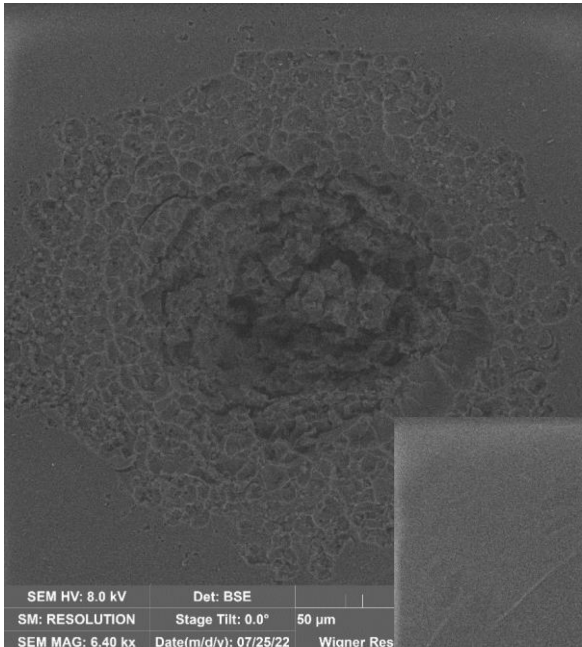

Volume: 3.5V$_o$
Volume: V$_o$
40 unit
40 unit

SEM IMAGE OF UDMA WITH AU NANORODS SEM IMAGE OF UDMA WITHOUT AU NANORODS
and Zygo images of the same craters

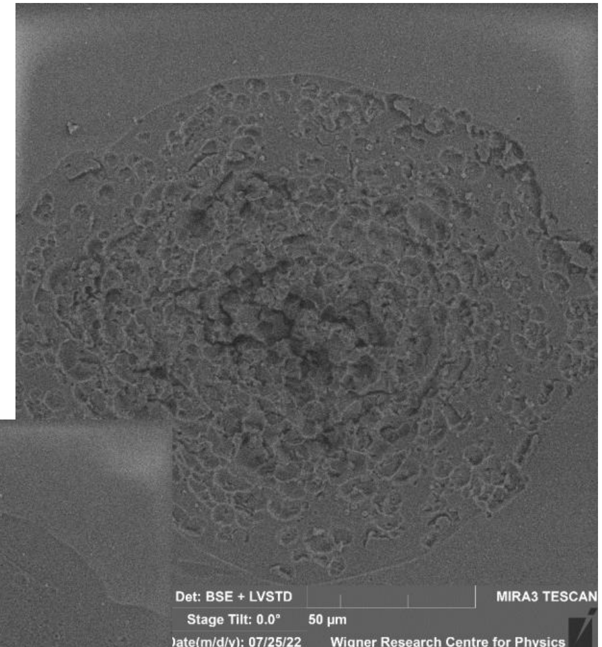




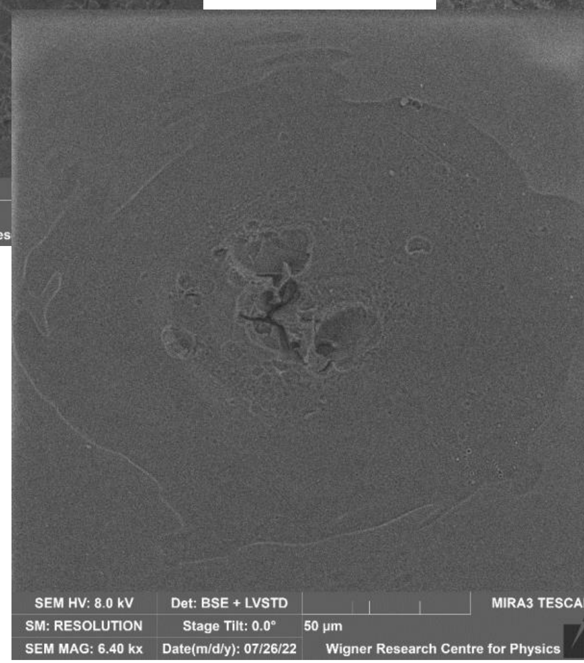
Images at 17.5mJ laser energy, $1{,}16.10^{17}$ W/cm² laser intensity.The volume of the crater of the sample with nanorods (b) is 1.98 times that of the sample without rods (a).


SEM HV: 8.0 kV
Det: BSE
SM: RESOLUTION
Stage Tilt: 0.0°
50 µm
SEM MAG: 6.40 kx
Date(m/d/y): 07/25/22
Wigner Res

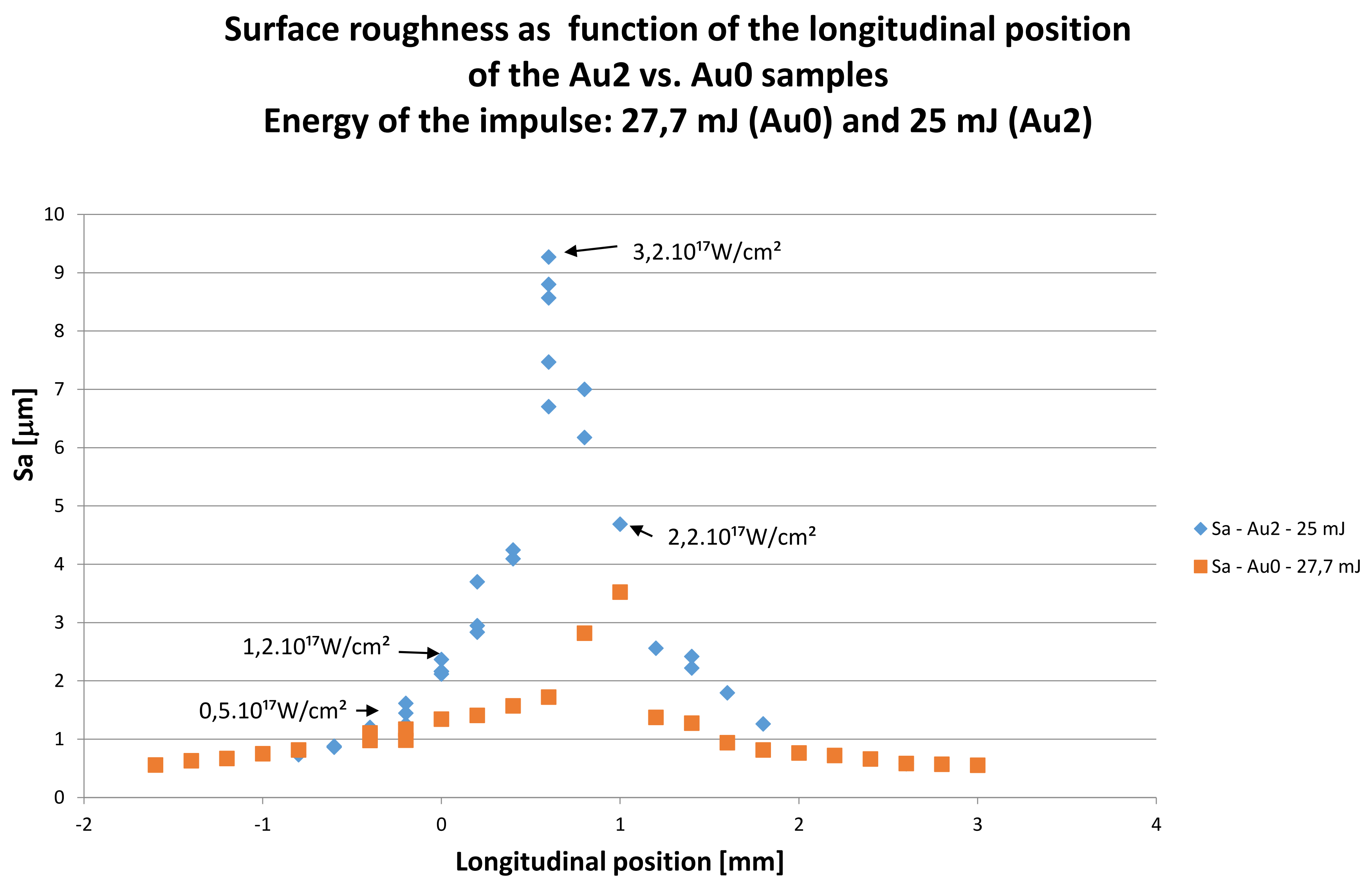
Au1


Det: BSE + LVSTD
MIRA3 TESCAN
Stage Tilt: 0.0°
50 µm
ate(m/d/y): 07/25/22
Wigner Research Centre for Physics

Au2

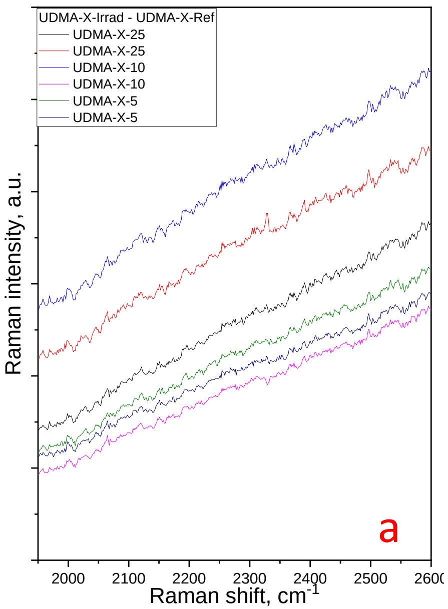

SEM HV: 8.0 kV
Det: BSE + LVSTD
MIRA3 TESCAN
SM: RESOLUTION
Stage Tilt: 0.0°
50 µm
SEM MAG: 6.40 kx
Date(m/d/y): 07/26/22
Wigner Research Centre for Physics

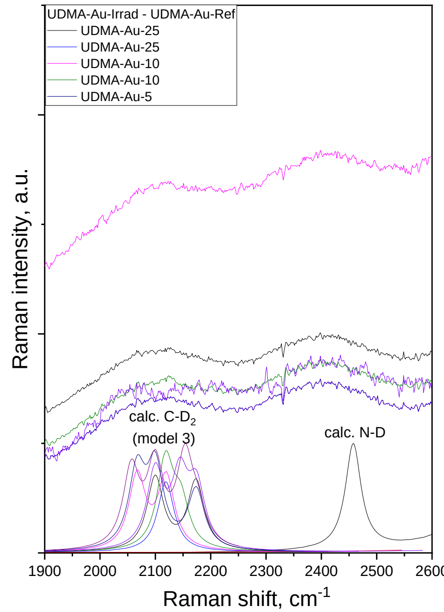
AuX

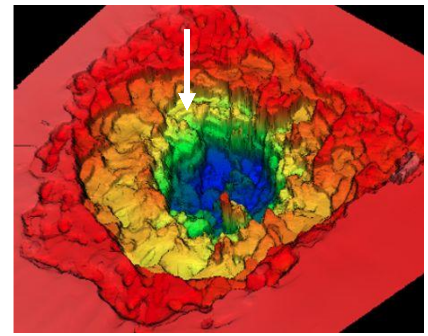

Surface roughness as function of the longitudinal position
of the Au2 vs. Au0 samples
Energy of the impulse: 27,7 mJ (Au0) and 25 mJ (Au2)
Sa [µm]
10
9
8
7
6
5
4
3
2
1
0
-2
-1
0
1
2
3
4
Longitudinal position [mm]
3,2.10¹⁷W/cm²
2,2.10¹⁷W/cm²
1,2.10¹⁷W/cm²
0,5.10¹⁷W/cm²
Sa - Au2 - 25 mJ
Sa - Au0 - 27,7 mJ

2.Diagnozis :Raman scattering from the crater surface

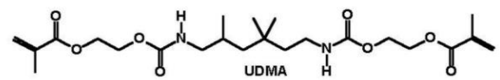
arXiv2210.00619(2022),submitted to Advanced Optical Materials

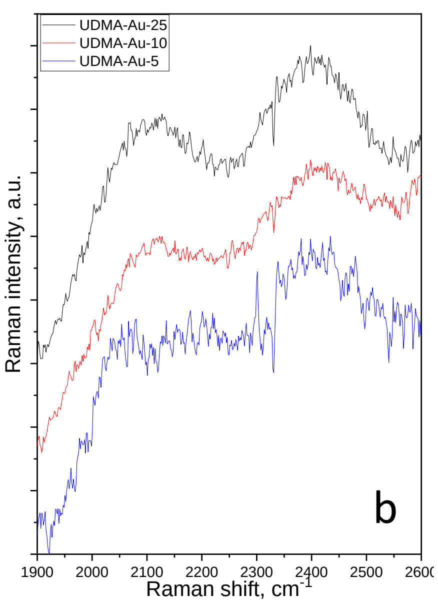


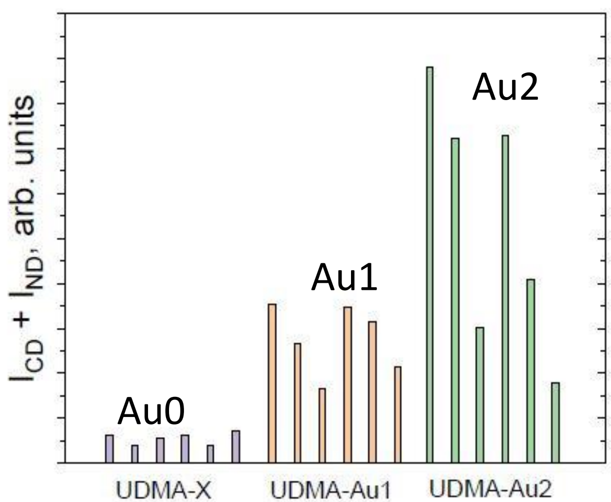


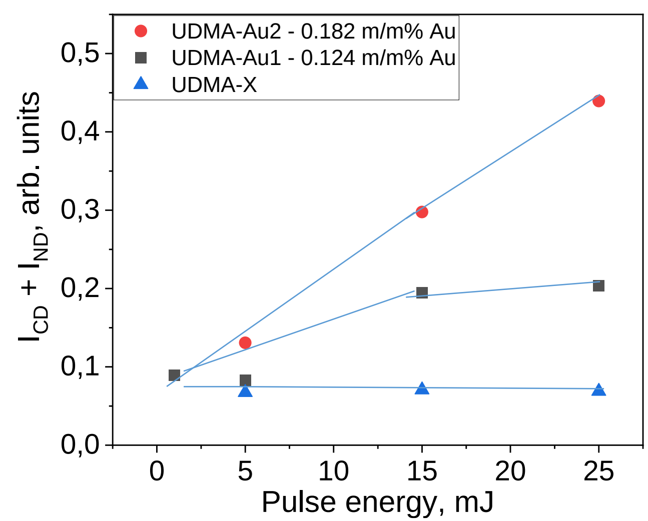


$I_{laser} > 10^{16}$ W/cm²







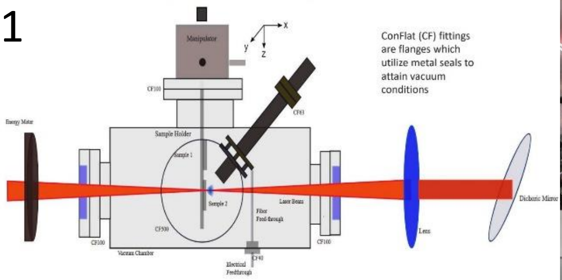


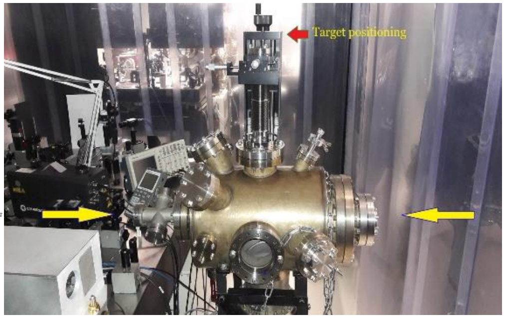
IN WORK BUT NOT YET CONCLUDING TECHNIQUES:

1. Atomic optical spectroscopy,
2. Mass spectrometry.
3. Nuclear detection techniques.

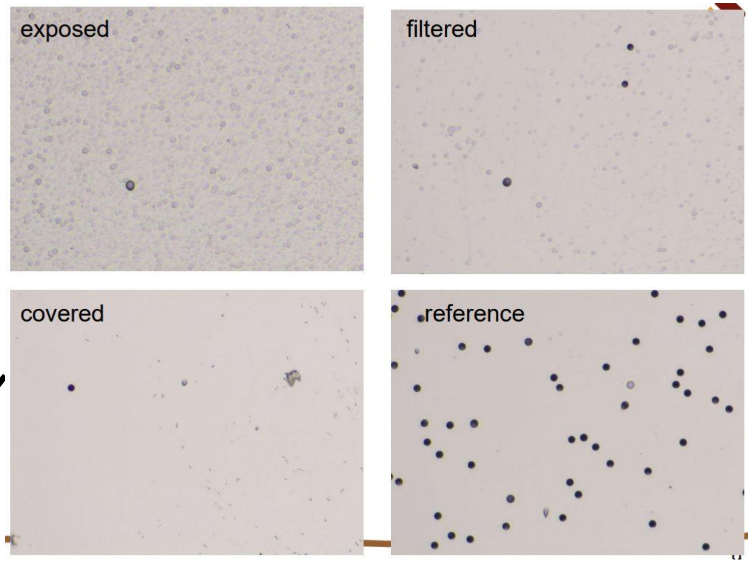
1

Experimental Setup for LIBS

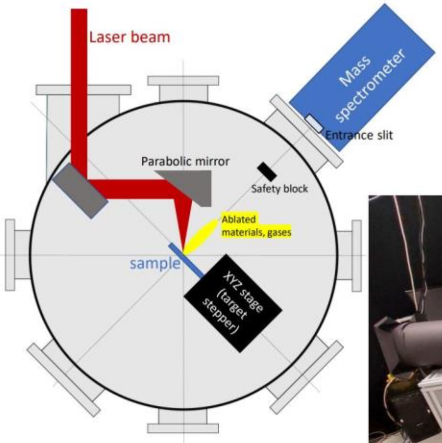




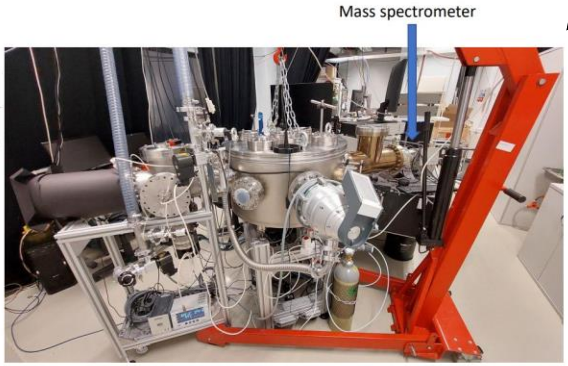
3: CR39 film, 1 laser shot



2

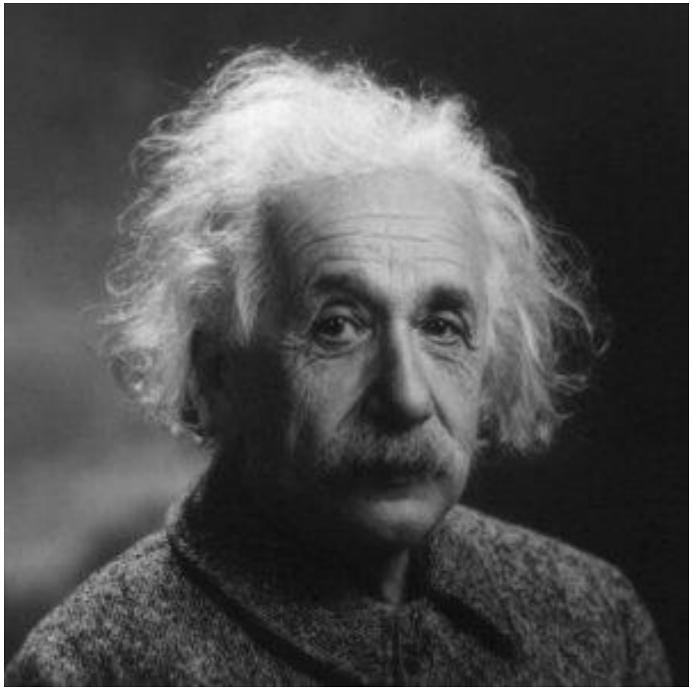


Experimental arrangement



THE ADVICE OF ALBERT EINSTEIN FOR THE FUTURE:

THE PROBLEMS WE ARE FACING TODAY CAN NOT BE SOLVED WITH THE SAME WAY OF THINKING BY WHICH WE CREATED THEM.



THIS IS WHY CREATIVE SCIENTIFIC THINKING IS THE KEY TO OUR FUTURE

THANKS FOR YOUR ATTENTION